ICASE

SEMIANNUAL REPORT

October 1, 1986 through March 31, 1987

INSTITUTE FOR COMPUTER APPLICATIONS IN SCIENCE AND ENGINEERING
NASA Langley Research Center, Hampton, Virginia 23665

Operated by the Universities Space Research Association

NASA

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

CONTENTS

INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and from industry, who have resident appointments for limited periods of time, and by consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

a. Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;

b. Control and parameter identification problems, with emphasis on effective numerical methods;

c. Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;

d. Computer systems and software, especially vector and parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period October 1, 1986, through March 31, 1987, is given in the Reports and Abstracts section which follows a brief description of the research in progress.

RESEARCH IN PROGRESS

Saul Abarbanel

Research followed three separate but not unrelated directions. In the research on deriving nonreflecting boundary conditions for the compressible Navier-Stokes equations (with A. Bayliss and L. Lustman), attention shifted to the wake problem, e.g., the flow past an airfoil whence the outflow numerical boundaries contain of necessity the wake. Decay rate and group velocity for the long waves were estimated for the low Mach number limit. Work is being continued to find numerical eigenvalues for the corresponding general case. At the same time, R. C. Swanson, Jr. (Transonic Aerodynamics Division, LaRC) is incorporating the new boundary conditions in an existing code to see if the expected benefits are realized.

In low Mach number flows, both the Euler and Navier-Stokes compressible code face a stiffness problem. Stability limits on the time steps (for explicit codes) are dominated by the speed of sound rather than the material problems. Work with D. Gottlieb and P. Dutt has resulted in a splitting algorithm which removes the stiffness and maintains the well-posedness of the problem. This is done via a transformation of the solution vector which allows symmetric splitting (i.e., all split matrices are simultaneously symmetrizable). Parts of the new algorithm may also be run in parallel thus enhancing its efficiency.

A method for predicting the enhanced convergence to steady state due to local time stepping has been developed for the time dependent two-dimensional convection-diffusion equation. Numerical tests to check the predictions are being designed. The method, based on examining the decay-rate of long waves, is in principle extendable to systems.

H. T. Banks and K. Ito

We are currently developing a theoretical framework for treatment of the LQG problem for distributed parameter systems involving unbounded input and observations in the state space. The approach employs sesquilinear forms and

allows one to develop approximation schemes for boundary feedback control in a number of important examples (e.g., the heat equation and the Euler-Bernoulli beam). In related but distinct investigations, we have developed a general framework for convergence and stability (continuous dependence of the estimates on the observations) in system identification problems using the theory of sesquilinear forms with the resolvent convergence form of the Trotter-Kato theorem. This theory offers the advantages (i.e., very weak compactness on the admissible parameter spaces) of a weak variational formulation and the advantages of the operator convergence form of the Trotter-Kato theorem (i.e., no smoothness assumptions on system solutions) without the disadvantages of either of these latter two approaches. The new theoretical framework can be used to treat a number of important examples (modeling various types of damping in beams, estimation of coefficients in Fokker-Planch and other parabolic systems including higher dimensional domain identification problems arising in thermal evaluation of materials).

H. T. Banks and F. Kojima

We are continuing our efforts on state estimation for vibrations of continuum structures (e.g., Euler-Bernoulli beams with tip bodies) subject to stochastic disturbances. Infinite dimensional filter equations for the systems have been derived, and we are currently investigating computational schemes to solve for the filters.

We are also continuing our investigations of inverse problems arising in thermal tomography. A particular model under study involves a 2-D heat diffusion system with unknown boundary (the domain identification problem) to be estimated from observations on part of the boundary. Both theoretical (convergence and stability of methods) and computational results have been obtained.

H. T. Banks and G. Propst

Together with R. Silcox (Acoustics Division, LaRC) we continue studying state space formulations of active noise suppression problems as optimal control problems governed by the wave equation. For several choices of the state space, the properties of the corresponding semigroups and their generators have been investigated. Boundary conditions on real or complex valued waves that model semireflection and phase shift are being identified by least squares parameter estimation procedures. The resulting model for duct acoustics will then be augmented by uncontrollable and controllable sound sources and the optimal feedback law evaluated by means of finite dimensional approximations.

H. T. Banks and I. G. Rosen

We have started to look at alternative models for heat conduction and the development of identification schemes for resulting inverse problems in conjunction with our involvement with the NASA nondestructive evaluation (NDE) group. Specifically, we are considering nonlinear heat conduction models, nonlinear distributed models for diffusion in fissured media, and hereditary or fading memory models involving distributed, integral history kernals. Our primary motivation in considering these alternatives to the conventional linear Fourier theory for heat conduction is to capture effects such as finite propagation speed and the perseverance of local singularities in material properties. At present, our research is primarily focused on modeling and theoretical issues such as well posedness and qualitative behavior of solutions. Future investigations involve approximation questions, parameter estimation, and numerical studies.

In addition to the work outlined above, we are also currently pursuing the extension of our identification procedures for one dimensional structures (i.e., flexible beams) to the estimation of elastic and viscoelastic damping parameters in two dimensional structures such as plates. We have also started to consider the modeling and identification of thermo-elastic effects in flexible structure dynamics.

Alvin Bayliss

Work continued in collaboration with L. Maestrello (Transonic Aerodynamics Division, LaRC), P. Parikh, and R. Krishnan (Vigyan Research Associates) and E. Turkel on the computation of three-dimensional spatially growing disturbances in a boundary layer. The computer code has been adapted from the VPS-32 to the Cray 2, and computations have been obtained for a highly unstable Reynolds number. An ICASE report is being prepared on these results.

The study of acoustic waves generated by unstable wave packets in a boundary layer over a curved surface with (L. Maestrello and P. Parikh) was extended by including convective terms in the analysis of the far field acoustic pattern and by the inclusion of symmetry boundary conditions to simulate a contraction section. An ICASE report is being prepared.

A new study was originated with D. Gottlieb, B. J. Matkowsky (Northwestern University), and M. Minkoff (Argonne National Laboratory) to develop appropriate functionals which measure the error in the pseudo-spectral approximation for certain classes.

Dennis W. Brewer

Research is continuing on parameter estimation problems associated with linear evolution equations in infinite-dimensional spaces. A general algorithm based on quasi-linearization has been established along with its local convergence properties. The algorithm has been numerically tested on linear delay-differential equations. Numerical experiments indicate that the method converges rapidly when used to identify two unknown delays together with two or three unknown coefficients using simulated data. Future research will involve continuing numerical experimentation and improvements in the theory to accommodate a wider class of problems.

Dennis W. Brewer and J. Steven Gibson

We are continuing our efforts to develop robust software routines for identifying parameters in robotic manipulators. The programs use numerical integration of nonlinear differential equation models and nonlinear optimization algorithms. This work is in conjunction with J. Pennington, F. Harrison, and D. Soloway (Information Systems Division, LaRC) who have provided experimental data. Our previous research indicates a need to model the integrated electro-mechanical system to reduce parameter sensitivity. We have obtained data and have tested models which include coupled physical and actuator dynamics. Good fits to experimental data have been obtained using these methods. Electrical parameters obtained in this way from on-line data agree well with the same parameters measured off-line. Future research will involve the simulation of multiple-link motions.

John Burns

The development of finite dimensional approximate models for control of infinite dimensional (distributed parameter) systems that govern various aerospace control systems has been the main focus of the present research. Most methods for constructing approximate models of systems of partial differential equations are based on some type of finite difference, finite element or Galerkin scheme. If such approximate models are to be used in control design and analysis, then it become essential to investigate these approaches to see if they preserve basic system properties important in control design. We have discovered that schemes that are excellent for simualtion may not preserve such properties as stabalizability and controllability. Moreover, some schemes can introduce extraneous eigenvalues that unnecessarily complicates the control design algorithm. Work is underway to understand the basic conditions that should be built into a computational algorithm that will guarantee pertinent control properties are preserved under approximation. Moreover, this problem is related to the question of robustness in that digital simulation of a control system requires that the model used in the design be at least as robust as the computer accuracy. Thus, part of the effort on this

project is devoted to the problem of developing numerical schemes that lead to finite dimensional approximations that are as robust as possible (e.g., the models should be as far away as possible from uncontrollable systems).

Tom Crockett

Several parallel algorithms proposed for the Flex/32 computer have demonstrated a need to lock individual elements of data arrays. Unfortunately, existing software for the Flex only supported locking of entire arrays, thereby preventing critical section operations on distinct elements from proceeding in parallel. To overcome this limitation, a package of subroutines was developed which provides an efficient locking mechanism for individual array elements. Performance measurements were obtained for these routines, as well as for a companion package of lock routines written by H. Jordan as part of the Force system. A by-product of these measurements was the discovery of an error in the NS32032 microprocessor which results in the suppression of timer interrupts during certain long string instructions.

Procedures were developed for accessing the Flex remotely from ICASE's Sun workstations, using Langley's high speed network connections and the Sun's windowing software.

I/O systems have frequently received inadequate attention in the design of parallel computer systems, resulting in bottlenecks and poor system utilization. In an effort to improve this situation, some initial work began on file concepts and access models for parallel I/O systems. Several types of parallel files were defined, based on their intended usages, and some potentially useful file partitionings were identified. It is hoped that the Flex computer can be used as a testbed for evaluating and refining these ideas.

Pravir Dutt and Nessan Mac Giolla Mhuiris

Much has been learned in recent years about the manner in which nonlinear but deterministic, finite dimensional dynamical systems can become chaotic. A

great deal has been written about the importance of this work to fluid dynamics though progress here has proved difficult. We are currently attempting to apply one tool from the finite dimensional arsenal, the powerful Melnikov method, to a class of inviscid, incompressible fluid flows known as the Kelvin Stuart catseye flows. The streamlines of these flows form heteroclinic orbits which repeat periodically in one spatial direction. Adding a marginally unstable mode to this system is equivalent to forcing the particle paths with a time periodic function. This is the classic scenario for an application of the Melnikov analysis. With this analysis, one can determine the manner in which the heteroclinic orbits get broken and this in turn can tell us whether the system becomes chaotic. Such Lagrangian chaos has been observed experimentally, and we hope to predict it with our work. Presently, we are devising a computer code to obtain the necessary marginally unstable mode.

Robert E. Fennell

Current research involves the development of control design methods for multivariable hereditary systems and is motivated by control design problems for flexible aircraft. Attention focuses upon robust control system design methods. Computational experience suggests that input/output models determined by observing the response of a linear, time invariant hereditary system to specified inputs are insensitive to measurement errors. Consequently, control laws based upon such plant representation should be insensitive to uncertain parameters. These ideas are being pursued in the analysis of feedback stabilization problems for hereditary systems. Related work with Bill Adams (Guidance and Control Division, LaRC) involves the design of robust control laws for flutter suppression and gust load alleviation of an aeroelastic vehicle. In addition, effort is being directed at the development of distributed control strategies for large scale systems.

James Geer

Research is underway involving the development and study of a hybrid perturbation/Galerkin method to determine how the method might be applied to some fluid dynamic and scattering problems. Several model problems involving singular perturbation expansions are being studied to help to better understand the method and to determine what type of problems to which the method might be applied. At present, these model problems include some linear and nonlinear two point boundary value problems with boundary layers (e.g., laminar flow in a channel with porous walls) and some simple exterior fluid flow and scattering problems involving very slowly converging perturbation series (e.g., acoustical scattering by a slender body). Work on the method itself is being done with Dr. Carl Andersen (College of William and Mary), while possible applications are being discussed with Dr. Eddie Liu (Low-Speed Aerodynamics Division, LaRC).

Another study involves the use of the symbolic computation system MACSYMA and perturbation methods to investigate some free and forced nonlinear oscillations. The method of multiple time scales has been implemented using MACSYMA and applied to the problem of determining the transient responses of the van der Pol and Duffing oscillators when the applied force consists of a sum of periodic terms with different frequencies. The conditions under which the system will experience frequency entrainment are being investigated. In addition, some very general stability results have been obtained for the free oscillations of a general nonlinear oscillator when the (small) nonlinearity is a polynomial function of the displacement and velocity. This work is being done with Dr. Carl Andersen (College of William and Mary).

Other research involves studying the possibility of using some of the ideas of uniform slender body theory for the problem of subsonic flow past a fully three-dimensional wing with sharp trailing edges and wing tips. A preliminary study is underway which will attempt to include trailing (wing-tip) vorticity effects on a three-dimensional thin wing with arbitrary planform. This work is being done with Dr. Eddie Liu (Low-Speed Aerodynamics Division, LaRC) and Prof. Lu Ting (New York University).

Investigations are underway concerning some fundamental properties (both from theoretical and computational points of view) of a class of "almost"

singular integral equations of the first kind which are useful in representing the solution to certain elliptic exterior boundary value problems. These equations typically have the property that the domain of integration R is a proper subset of the domain of validity D of the equation. Special consideration is being given to the idea of analytically continuing the solution into the domain D. In fact, this has now been done for a large class of one dimensional integrals, such as those which occur in the representation of solutions involving a body of revolution. For this special class, a characterization of R in terms of certain properties of the analytic continuation of the kernel has been obtained. This characterization leads to a simple numerical procedure to determine R and helps to circumvent some of the stability problems inherent in solving integral equations of the first kind. Applications of the results will be useful in several two- and three-dimensional problems involving slender or thin bodies. The symbolic manipulation system MACSYMA has been used in some of the preliminary investigations.

J. S. Gibson and I. G. Rosen

Our efforts have been concentrated on the development and study of finite dimensional approximation schemes for the solution of the optimal Linear Quadratic Gaussian (LQG) control and estimator problems for distributed parameter and delay differential systems with unbounded input and output. More specifically, we have been looking at systems involving boundary control, input and output delays, and unbounded measurement. Functional analytic, or more precisely, semigroup theoretic convergence arguments for spline and modal based finite element approximations to optimal control and estimator gains have been established. Extensive numerical studies for heat/diffusion systems with both Dirichlet and Neumann boundary control and pointwise state observation have been carried out. Flexible structure examples involving cantilevered beams with a shear or bending moment input at the free end and pointwise observation of strain or acceleration are currently under study.

David Gottlieb

We continue to develop the theory for spectral approximation to problems with discontinuous solution. We have extended the Mock-Lax theory to collocation methods and proved weak convergence for pseudospectral methods. This result enables us to extract spectrally accurate pointwise values from numerical approximations that use pseudospectral methods. The above results show how to get high order accuracy away from a discontinuity; however, these techniques amplify the oscillations in the neighborhood of the shock. We have developed now a technique to reduce those oscillations. The combined method is being tested in the context of an astrophysical problem (jointly with E. Tadmor).

We suggested a new splitting method for low Mach number flows. This splitting is the only one known to us that keeps the Euler system of equations symmetric (jointly with P. Dutt and S. Abarbanel).

We continue to work on boundary conditions for multidomain techniques applied to hyperbolic equations. We check the possibility of satisfying both the differential equation and the boundary conditions at the boundaries. This procedure seems to guarantee stability (with D. Funaro).

Chester E. Grosch

We have completed the development and testing of the three-dimensional, time dependent Navier-Stokes code in vorticity and velocity variables in collaboration with T. Gatski (High-Speed Aerodynamics Division, LaRC) and M. E. Rose. This work is now being written up for publication. R. Spall (Old Dominion University) has completed his study of vortex breakdown using this code. Spall, Gatski, and Grosch have reported on the Rossby number correlation for vortex breakdown in ICASE Report 87-3. Finally, we are using this code to study boundary layer receptivity and are planning to use it to study the dynamics of horseshoe vortices.

Calculations of the stability of a family of vortex flows, which are exact solutions of the Navier-Stokes equations, is continuing with M. Korami (Old Dominion University). We expect that the results of these calculations will

illuminate the dependency of the stability or instability of these flows on the Reynolds number and pressure gradient.

The study, in collaboration with R. Fatoohi, of parallel algorithms for elliptic and parabolic partial differential equations is continuing. A short paper, reporting on the results of the implementation of parallel/concurrent algorithms for the elliptic problem on the MPP, FLEX/32, and CRAY/2, has been accepted for presentation at the 16th International Conference on Parallel Processing. A complete report of this work is being prepared for journal publication. The work on the parallel/concurrent algorithms for the parabolic problem is continuing.

S. I. Hariharan

Work on atmospheric acoustics is being continued. Theoretical aspects are covered in a recent report with P. K. Dutt (ICASE Report No. 87-19). Currently computational work is being done to demonstrate the nonlinear behavior of the atmospheric wave propagation. Additional theoretical considerations needed are nonlinear energy estimates and higher order boundary conditions that support these estimates. They are currently being investigated.

The goal of acoustic interactions in compressible viscous flows is to understand the effect of acoustic waves in compressible viscous subsonic media, in particular, the effect of acoustic waves in boundary layers. At this stage, the experiments are purely numerical. A typical configuration of the flow past a semi-infinite flatplate is being considered. The current status of the work is as follows: A compressible Navier-Stokes code has been built to handle flows that are not necessarily parallel flows. Upstream conditions and a nonreflective downstream condition are prescribed to emulate a realistic situation. The flowfield is developed with a set of appropriate initial conditions. Effectiveness of the code has been verified for the case of parallel flows by comparing with the Blasius solution. Also, introducing discontinuities in the initial temperature field generates acoustic waves. The results seem to be realistic. Further investigations are being carried out to understand the nature of these acoustic waves. Moreover, acceleration

of computations is being considered. In particular, the recently introduced nonreflective boundary conditions of Abarbanel, Bayliss, and Lustman (ICASE - Report No. 86-9) are being incorporated.

Tom L. Jackson

Experimentally, as a turbulent deflagration wave accelerates in a gas tube, it creates a shock wave ahead of it. Somewhere between the flame and shock wave a "hot spot" develops, eventually leading to a reacting blast wave. If the strength is sufficiently large, the blast wave overtakes the shock, leading to the formulation of a detonation wave. We continue our investigation into the birth process of hot spots in reacting gases. Recently, the spatial structure and temporal evolution of interior and boundary "hot spots" have been examined (ICASE Rep. No. 87-2). We are currently investigating several numerical and analytical methods to develop the solution further in time, describing the eventual development of a detonation wave. This work is being done in collaboration with A. Kapila.

A current research effort at LaRC is the study of supersonic combustion flames (detonation waves) in the context of the scramjet engine, used in the propulsion of hypersonic aircraft and cruise missiles. An important aspect of the combustor design of the engine lies in understanding the influence of turbulence upon a detonation wave, and hence upon chemical mixing. We are currently working on a model which describes the response of a steady detonation wave to finite amplitude, time-dependent disturbances. This work is being done in collaboration with A. Kapila and M. Y. Hussaini.

Harry Jordan

A complete and efficient version of the Force parallel programming extension to Fortran is now running smoothly under the Flexible Computer Corporation's Flex/32 system at LaRC. Two further developments have received attention in the last half year. The Force is being integrated into T. Pratt's

PISCES parallel programming system underneath the parallel task and cluster computational model used in that system. Perhaps surprisingly, the fact that the Force assumes a somewhat constrained parallel operating environment does not seem to interfere with its integration into a fairly different parallel computational model. The reason is probably the relative simplicity of the Force computational model, which is also the reason why minimal difficulty was encountered in producing a relatively smoothly operating Force system using a fairly preliminary version of the Flex/32 operating system.

The second line of development is to use the Force to produce parallel versions of structural analysis programs. Both routine parallelization of existing modules from the NICE/SPAR structural analysis package as well as the development of new parallel algorithms is being supported. G. Poole (University of Virginia) has been using the Force in some work on linear system solvers, and N. Arenstorf (University of Colorado) has produced a parallel version of part of the linear system solver in SPAR. Since the SPAR system is not yet running as a whole under the MMOS parallel operating system of the Flex/32, the generation of a good test interface for the parallel module presents a challenge.

David Kamowitz

Work continues on developing a parallel multigrid algorithm for the solution of the steady state elasticity equations. The domain of interest is a thin plate with holes and cracks. Of particular interest is the use of overlapping meshes to improve the resolution of the solution near singularities. The use of overlapping meshes suggests using either the Full Approximation Scheme (FAS) of A. Brandt or the Fast Adaptive Composite Grid (FAC) method of S. McCormick. Both of these algorithms are being tested for the solution of this problem.

Two levels of parallelism are present in this problem. The first level consists of solving the problem on each mesh independently and then using each solution to update the solution on the other grids. The solution on each mesh can be done in parallel with the solution on the other meshes. This leads to

a variant of block Gauss-Seidel and is also the core of the FAC method. The second level consists of exploiting the local nature of the equations on each grid and to use a parallel algorithm for the solution of each subproblem. These two approaches are being considered for implementation on the Flex/32 multicomputer.

Steve Keeling

There are two areas of activity. First, some active noise suppression projects are coming into sharper focus through interaction with the Acoustics Division at LaRC. Also, work is continuing on Galerkin/Runge-Kutta methods for evolution equations.

Implicit Runge-Kutta methods have very attractive properties with regard to stability and implementation. However, some unusual consistency characteristics are becoming well-known. Specifically, if an IRKM with classical order $v > 1$ is used to solve a test problem for which order v is observed, a serious order reduction can be observed for a more complicated problem, even if the solution is infinitely smooth. The proofs show that in addition to being smooth, the solution should be in the domain of powers of the elliptic operator, as for example, solutions of the heat equation are. Nevertheless, while there is interest in sharpening theorems which predict convergence rates, I have found a systematic way of modifying any IRKM so that high order convergence can be proved without restrictive conditions on the solution. Furthermore, the computational evidence continues to show that these modified methods offer not only optimal order convergence but accuracy exceeding that achieved by their unmodified counterparts.

Fumio Kojima

We continue to investigate the numerical technique for the identification of boundary value problems in several spatial dimensions. Although the reduction of elliptic (resp. parabolic) boundary value problems to equivalent

boundary integral equations is historically well-known, its numerical exploitation has been recently developed. Our interest is concerned with the design and the analysis of system parameter estimation provided with the high numerical accuracy and with the theoretical convergence property for finite approximation schemes. By using finite element approximations on the boundary, several methods for estimating unknown parameters are proposed.

Also, we are continuing our efforts to develop the finite approximation technique of the identification for stochastic distributed parameter systems based on the maximum likelihood estimation.

W. D. Lakin and P. Hall

The fully nonlinear development of small wavelength Görtler vortices in growing boundary layers is investigated using a combination of asymptotic and numerical methods. The development of the theory is unusual in that the nonlinear stability is not described by the Stuart-Watson approach. Rather, the development is governed by a pair of coupled nonlinear partial differential equations for the vortex flow and mean flow correction. It is found that the mean flow correction driven by large vortices can be as large as the basic state, yet can still be described by asymptotic means. It is shown that the vortices spread out across the boundary layer and effectively drive the boundary layer. Indeed, the new basic state cannot be obtained independently, but is determined from a differential equation generated by the equations for the fundamental component of the vortex disturbances. The mean flow adjusts so as to make these large amplitude disturbances locally neutral. In the region where the vortices exist, the mean flow is found to have a "square-root" profile which has essentially no relationship to the flow which exists in the absence of the vortices.

Chris C. H. Ma

A modified version of the generalized self-tuning regulation methodology of Elliott, Wolovich, and Das has been applied to a 26-state model of the SCOLE system. The objective has been to evaluate the asymptotic performance of such adaptive control methodology on a complex system.

In the very first simulation, the 26-state model was truncated to 10-states, and convergence of the adaptive system was successfully achieved on the ICASE SUN 3/180 computer. The adaptive controller obtained was found to have parameter values ranging from 10^{-5} to 10^{12}. However, further simulations with the SCOLE model states increased to beyond 10 were found to be non-convergent due to a numerical problem. The so-called "covariance matrix" in the recursive least-squares identification algorithm used, which should stay symmetric positive-definite regardless of the performance of the adaptive methodology used, was found to have negative values in the diagonal every time the experiment was nonconvergent.

Various procedures have been taken in attempt to correct the above numerical problem, including resetting the "covariance matrix" upon detection of the non-positive-definiteness and simulating the adaptive system on the numerically more precise (64 bits) NASA CYBER 170 computer. Covariance resetting has been found to be futile for correcting the above problem. However, the simulations have resulted in observable transient performance improvements.

Simulation of the adaptive system on the NASA CYBER computer will be continuing until a more confident conclusion on the convergence property of the generalized self-tuning regulation methodology can be obtained. Meanwhile, the problem of adaptively controlling the dynamics of a robot manipulator will be investigated.

Nessan Mac Giolla Mhuiris

An attracting set for a dynamical system is a region in phase space which "attracts" nearby initial conditions. Any orbit started in the neighborhood of such a set, A, will evolve towards it and not leave A thereafter. Attracting sets for dissipative systems have dimensions which are less than

those of the phase space as a whole and, as they eventually trap all initial conditions, it is their character which governs the long term, asymptotic behavior of the system. Recently, examples have been found of some remarkable attractors. These strange attractors are characterized by the fact that orbits in them, which at some time lie infinitely close together, diverge from each other at an exponential rate and become uncorrelated in a finite time. In effect, this precludes quantitative predictions of the behavior of individual orbits for all but the briefest times. Such behavior, termed sensitive dependence on initial conditions, must be present if the system is to be considered chaotic.

Many finite dimensional flows are now known to have this sensitive dependence on initial conditions, and it has been conjectured that the appearance of strange attractors is responsible for the evolution of turbulent fluid flows from their laminar percursors. A study is underway to address this conjecture. The rates at which nearby orbits diverge or converge for a given vector field is termed the Lyapunov spectrum of the flow. A strange attractor must have at least one positive and one negative Lyapunov exponent. A new method of measuring these exponents for the incompressible Navier-Stokes equations has been formulated. This method is capable of measuring both positive and negative exponents. Currently, it is being applied to the case of spatially periodic flows in a cube.

Nessan Mac Giolla Mhuiris and Yousuff Hussaini

There has been much conjecture of late about the role of helicity in the flow of turbulent and preturbulent fluids. Alignment of a vortex line and a streamline causing a stretching of the vortex line has been seen as a mechanism to locally increase the vorticity in a fluid flow. Indeed, it has been suggested that in certain cases, turbulent fluids can be in a state of Beltrami flow for a long time with the vorticity and the velocity becoming completely aligned. However, the nonlinear diffusive terms in the Navier-Stokes equations are not present for Beltrami flows. To study the importance of this mechanism, the flow of an incompressible fluid in a periodic cube is

being investigated numerically. A highly accurate divergence free spectral method is being used to solve the equations, and careful attention is being given to the angles between the vortex and stream lines. In this manner, we can track the evolution of any areas in the fluid which become Beltrami-like over time.

Dimitri Mavriplis

The use of unstructured meshes for solving steady inviscid compressible flow problems about complex configurations is being investigated. At present, solutions have been restricted to multi-element airfoils in two dimensions. A multigrid algorithm has been developed for solving the steady-state Euler equations in two dimensions on unstructured triangular meshes. The method assumes the various coarse and fine grids of the multigrid sequence to be independent of one another, thus decoupling the grid generation procedure from the multigrid algorithm. The transfer of variables between the various meshes employs a tree-search algorithm which rapidly identifies regions of overlap between coarse and fine grid cells. Finer meshes are obtained either by regenerating new globally refined meshes, or by adaptively refining the previous coarser mesh. This is achieved by locally adding points in regions where large flow gradients are observed and retriangulating. For both cases, the observed convergence rates are comparable to those obtained with structured multigrid Euler solvers. The adaptively generated meshes were found to produce solutions of higher accuracy with fewer mesh points. This work resulted in a paper, co-authored with A. Jameson, which was presented at the Third Copper Mountain Multigrid Conference in April of 1987.

Further research is aimed at optimizing the amount of work performed on each grid of the adaptively refined multigrid sequence. One approach being considered involves confining the fine grid time-stepping to the regions of the mesh which have been locally refined. Another possibility involves time-stepping on the entire fine mesh but omitting the time-stepping operation on regions of the coarse mesh where the mesh point distribution is not appreciably sparser than the previous fine mesh.

Navier-Stokes solutions are also being pursued. Preliminary work has begun with the generation of Navier-Stokes-type meshes about single airfoil geometries. The unstructured multigrid algorithm is expected to carry over to Navier-Stokes problems in a straightforward manner. However, the generation of suitable Navier-Stokes meshes about complex configurations is a non-trivial problem which will require further research.

Piyush Mehrotra and John Van Rosendale

In the last six months, work on the BLAZE language has focused on understanding the issue of shared versus non shared-memory, and the language level implications of this architectural choice. A recent paper on automated domain-decomposition techniques focused on this issue, in the context of BLAZE compiler transformations. This work was primarily directed towards architectures, like the IBM RP3, in which memory locality is important, though shared memory semantics are still supported.

We are in the process of extending this work to non shared-memory architectures. While exploiting locality and minimizing communication seem important on all parallel architectures, on non shared-memory systems, they are critical. It is not clear whether BLAZE-like languages, in which the programmer can easily write algorithms requiring massive communication, are well suited to non shared-memory architectures. L. Snyder (University of Washington) has been suggesting the use of APL-style languages in this context. This is an alternative we are actively exploring.

We have also been continuing development of synchronized packet interconnection networks and of heterogeneous architectures based on this concept. The idea here would be to provide a set of compatible hardware-software modules, which one could assemble into "special purpose" architectures for specific applications. Each module would be viewed as an "abstraction" or "object" at the language level.

This approach is similar to the use of attached vector coprocessors for linear algebra kernels. We are simply pushing this idea further, suggesting its use as the organizing principle for the entire architecture and program-

ming environment. One kind of module being devised would be a "continuous function" module, which would contain, and allow one to manipulate, spline representations of continuous functions. There is a substantial benefit to building spline representations into hardware, though there is also a loss of flexibility and programmability.

David Middleton

Research in parallel computing proceeds in several directions, three main ones being algorithm design, language design, and hardware design. There are many criteria for evaluating design choices in these areas, and these criteria have subtle and extensive interrelationships, both within a single area and between separate ones. There is little agreement among researchers as to how conflicting criteria should be weighed, especially between the separate areas. One such difficulty lies in balancing the flexibility to be gained through generality with the efficiency to be gained through restrictions of the problem domain. I am investigating some problems which involve balancing criteria from these areas.

One such conflict exists between the need of parallel languages for inexpensive task creation and the difficulty for hardware in providing it. One approach is to create new virtual machines during execution as is done on the FFP Machine. The FFP is a fine-grained MIMD parallel computer that has been designed to execute the functional languages of John Backus. As an available task is detected during execution, a group of dedicated hardware resources is rapidly allocated for its evaluation in a way that avoids alignment and fragmentation problems.

Backus's FP was designed to provide certain elegant language properties which allow programs to be manipulated and reasoned about algebraically. Certain algorithms, however, appear difficult to implement efficiently in FP. A family of algorithms called parallel prefix operations has received much attention lately, and I have been investigating implementing them efficiently in FP, where the efficiency is measured specifically with regard to the model of computation provided by the FFP Machine. Some particular parallel prefix

operations, being necessary to support certain system operations, have been part of the FFP Machine from early on. As a first part of this study, I have developed a generalization of the hardware support provided by the FFP machine's switching network for these parallel prefix operations.

Given the FFP Machine as a hardware design that has been derived from the FP language, it is interesting to see how well the FFP machine can implement other languages. Research with B. Smith (Indiana University) is examining implementing the OPS5 Production System language on the FPP machine. This study may shed light on disagreement that exists as to the practicality of fine-grained machines for OPS5.

The Navier-Stokes machine is a hardware design that has been derived from the needs of a specific algorithm. An interesting research direction is to examine how well languages and programming aids may be created to support such a machine after the hardware design has been completed (perhaps by importing techniques from other systems such as the BULLDOG compiler technology for VLIW architectures).

Vijay K. Naik

Work is continuing towards developing methodologies that will characterize MIMD architectures and quantify the architecture and algorithm dependent parameters. We are concentrating mostly on problems relating scientific computations, although the principles developed here should be applicable to other appropriate areas of parallel processing as well. Various existing as well as proposed architectures and important algorithms are currently under investigation. It is hoped that the outcome of this research will help towards automating the process of efficient parallel implementations.

David M. Nicol

Two model problems, one from fluids dynamics using dynamic regridding, and the Game of Life, have been implemented on the FLEX/32 and an Intel Hypercube

for the purpose of empirically studying dynamic load balancing policies. These codes will serve as a testbed for (1) centralized, static "risk averting" policies, (2) dynamic scheduling of risk averting policies, (3) dynamic remapping of exact balance policies, (4) decentralized balancing policies. The simplicity of the model problems should allow a comparative study between these various methods. This work is being done with J. Saltz.

We continue to develop analytic models which describe the behavior of dynamically evolving computations. We have recently been able to capture the phenomenon of correlation between pieces of work, derive the optimal static mapping of such workloads, and discuss optimal scheduling of dynamic remapping of these workloads. Further work will attempt to generalize this model. This work is being done with J. Saltz.

We are porting a subset of the ABL's CORBAN simulation to the FLEX/32. Once implemented this distributed simulation testbed will allow a study of the effectiveness of various load balancing policies and will also allow a comparison of various synchronization protocols which have been proposed in the literature for distributed simulation. This work is being done with J. Saltz, P. Reynolds, and F. Willard.

One problem which is often overlooked in parallel processing is the determination of the number of processors to employ in solving a problem. Increasing the number of processors can improve parallelism while increasing overhead costs such as communication. We have analytically captured the relationships between execution and communication costs in order to determine an optimal allocation of processors to a given task in a given architecture. We are currently validating our analytic models on the FLEX/32.

We are attempting to explain the run-time behavior of backtracking search, using the N-Queens problem as a model. Two different methodologies have been developed for estimating the number of search tree nodes visited during a search; an optimality proof for one model of the "most-constrained" dynamic search rearrangement strategy has also been constructed, and the analytic model has been validated on a variety of backtracking problems. Further work will attempt to extend our analytic and empirical results. This work is being done with Harold Stone.

Merrell L. Patrick

Computing systems of the future for large scale scientific and engineering computations will consist of many processors and memories working in parallel to solve a single problem. Efficient use and ease of use of these future systems are two basic problems facing potential users. The development of new parallel algorithms, parallel execution time models which predict the performance of the algorithms on different parallel architectures, and parallel programming environments for expressing the algorithms are essential for progress toward the solution of these problems.

Development of parallel algorithms and corresponding parallel execution time models for solving the generalized eigenvalue problem is continuing. Results from the models will be used to predict the performance of the algorithms on message passing and shared memory MIMD machines. The parallel algorithms will be integrated into a structural analysis system, NICE/SPAR, running on the FLEX/32 as a program module used in the dynamic analysis of a structure in motion. Algorithms based on subspace iteration and Sturm sequences have been implemented and tested on the FLEX/32 at LaRC. Efforts continue to determine the algorithm of choice for bus-based architectures such as the FLEX/32.

The algorithm of choice will be used as a basis to continue work with T. Pratt and H. Jordan on defining the essential ingredients of parallel programming languages for scientific computations. Different programming paradigms will be used to program this algorithm on the FLEX/32 system and the overhead of the different implementations will be compared.

Work with L. Adams and D. Reed determined optimal stencil/partition pairs for solving elliptic partial differential equations on MIMD machines. The optimality condition was to maximize the computation to communication ratio. Parallel execution time models were developed for message passing and shared memory architectures to predict the impact of the architecture on the choice of stencil/partition pairs.

A study to extend these models to include the impact of input/output on performance of parallel systems has been initiated with D. Reed. A long range planning document for multidisciplinary studies in the use of emerging parallel computers in the aerospace sciences has been written with J. Ortega and R. Voigt.

A study with J. Saltz and R. Voigt which attempts to answer the question as to whether SIMD architectures are sufficient for carrying out many of the computations arising in the solution of partial differential equations is still planned.

Doug Peterson

Two additional Sun 3/50 diskless workstations have been added to the ICASE computing environment, bringing the total number of workstations supported by the file server to fourteen. Additional building wiring has been installed to provide direct MICOM access from each of the workstations, thus easing load on the file server. Release 3.2 of Sun Microsystems operating system has been installed and is performing satisfactorily. Full access to ARPANET sites is available from the Sun file server. The floating point accelerator module has been delivered and installed in the file server and performs as specified. The IBM PC/AT´s in the ICASE office have been networked with the Sun file server through ethernet, using Sun Microsystems PC-NFS software.

The locally prepared document "Computing at ICASE" has been revised to reflect changes in the ICASE computing environment. Except for graphics, this document was prepared on the Sun using available UNIX editors and document formatters. As in the past, the graphics were done using a Macintosh.

An effort is currently in progress to upgrade the document publising capabilities at ICASE. Systems being evaluated include WYSIWYG systems, word processors, and text editors in conjunction with document formatters. The goal of this effort is to provide a complete document preparation and publishing system capable of integrating text, mathematical equations, and graphics from a wide range of input formats, including hand-written rough drafts and those prepared at other sites and transmitted to ICASE electronically. Additionally, the system should be able to support several output formats for electronic transmission to technical journals. Products from several vendors have been evaluated in-house. Some have deficiencies in areas of compatibility with existing systems; other products lack mature capabilites in certain areas. The document formatting system TeX, as distributed by the University of Washington, has been installed.

ICASE has participated in the development of a center-wide TCP/IP network at Langley, with the Sun file server playing a key role. ICASE has provided technical support through consultation in all aspects of UNIX including network design, management issues, communications protocols, IP internet addressing, establishment of reliable electronic mail, user training, and system administration. This effort has resulted in the adoption of TCP/IP as the primary computer network protocol at Langley Research Center.

Terrence W. Pratt

The PISCES 2 parallel programming environment allows the scientific programmer to write parallel programs that are intended to run on various parallel architectures. Programming is done in Pisces Fortran, an extension of Fortran 77 that includes constructs for controlling a parallel computer. Several "granularities" of parallel operation are provided.

Pisces Fortran includes a version of the "force" constructs developed by H. Jordan. It also provides features for defining tasks and sending messages asynchronously.

The PISCES 2 environment inclues (1) a preprocessor that translates Pisces Fortran into standard Fortran 77, (2) a configuration environment that allows the programmer to set up a run on the parallel machine, and (3) a run-time environment that allows the programmer to monitor and control program execution. A library of run-time routines is used to implement the various Pisces Fortran language constructs.

The PISCES 2 environment is running on the FLEX/32 at LaRC. Current work involves measuring the performance of the system to determine the software overhead for use of the various language constructs.

Joel H. Saltz

It is anticipated that in order to make effective use of many future high performance architectures, programs will have to exhibit at least a medium

grained parallelism. Methods for aggregating work represented by a directed acyclic graph are of particular interest for use in conjunction with techniques under development for the automated exploitation of parallelism.

An investigation has been carried out into methods appropriate for the aggregation, mapping, and scheduling of relatively fine grained computations specified by a directed acyclic graph. The solution of very sparse triangular linear systems provides a very useful model problem for use in exploring these heuristics.

A number of questions that relate to partitioning the work required to solve sparse triangular linear systems is consequently explored. A method is described for using the triangular matrix to generate a parameterized assignment of work to processors, and simple expressions are derived that specify the scheduling of computational work. The tradeoffs between load imbalance and synchronization costs as a function of two orthogonal measures of granularity, **block size** and **window size** are examined experimentally on an Encore Multimax shared memory machine, an Intel Hypercube as well as analytically in the context of a model problem. The results of these studies are to be presented in an ICASE report and are being used in a modeling study with D. Nicol.

Joel H. Saltz and David M. Nicol

We consider the tradeoffs between the benefits and costs of balancing load in multiprocessor solutions of computational problems that describe the evolution of a physical system over the course of time. The type of architecture being assumed is one in which each processor has a local memory and the processors pass messages through either a communications network or a shared memory. The responsibility for computations pertaining to a given portion of the problem domain is assigned to each processor. The data dependencies inherent in the solution of a time dependent problem cause the most heavily loaded processor to limit the rate at which the problem is solved. Frequently, the load in the portion of the problem assigned to each processor will vary, and without redistribution of load, system performance declines. While

performance can be improved by a redistribution of load, this redistribution itself exacts a sometimes large delay cost.

Two probabilistic load models are proposed and used to evaluate policies for deciding when load balancing should be performed. Through use of these models, it is possible to characterize the relative performance of a number of different policies designed to determine when load should be balanced. This performance characterization is carried out through the derivation of analytic expressions and through simulation. Estimates of how the cost of balancing load interact with model parameters describing the number and activity of processors are obtained. Validation of these results is being carried out using an Intel iPSC hypercube implementation of Conway's Game of Life and a Flex/32 implementation of a fluids code.

In a separate but related activity, a study is made of tradeoffs between communication costs and load imbalance in multiprocessors with preferential access to local memories, and between synchronization costs, and load imbalance in machines where the access time to all memory is approximately equal. Both analytic modeling and empirical studies on the Intel iPSC hypercube and the Encore multimax are carried out. The problem used in the empirical studies is that of solving sparse linear systems arising from finite difference discretizations of elliptic partial differential equations. The method used to solve these systems is a conjugate gradient type method, orthomin, preconditioned with incomplete LU factorizations. Wavefront methods are used to obtain parallelism in the forward and back solve of the sparse lower and upper triangular matrices required for preconditioning.

Parametrized mapping schemes are developed that allow one to adjust the granularity of parallelism in several different ways. The mapping chosen influences both the balance of load and the communication and synchronization overheads observed. The experimental results will be compared with analytic models of these tradeoffs in a particularly regular model problem as well as more general probabilistic models of these tradeoffs.

Paul Saylor

The Chebyshev method with the adaptive algorithm of Manteuffel is an iterative method for the solution of nonsymmetric systems. The package form of the method is called Chebycode. There are many other methods for nonsymmetric systems such as ORTHOMIN, but there is no public domain package incorporating non-Chebyshev methods. Discussions have been held with W. Whitlow (Loads and Aeroelasticity Division, LaRC) on the applicability of Chebycode to the Approximate Factorization method, which is an unaccelerated iterative method that converges rather slowly. The Approximate Factorization method is part of a code for the solution of the Transonic Small Disturbance equation.

CGCode is a package of conjugate gradient methods suitable for either symmetric positive definite or symmetric indefinite systems. Preconditioning is allowed in a way convenient to the user. The package has been discussed with J. Newman (Materials Division, LaRC) and I. S. Raju for use on large matrices with a bandwidth of 10000 or more where direct methods are not practical.

Another activity is focused on "leapfrog iterations." This work is the basis of an ICASE report, nearly complete, on some techniques to avoid I/O and to facilitate chaining, when appropriate, for the solution of large problems by rearranging the computation. Preconditioning can also be done. The algorithm should be useful on supercomputers with or without large memory.

Richardson's method requires a set of acceleration parameters, and in most of the work these parameters are assumed to be known. However, this effort is focused on providing a computational method for computing the parameters based on the least squares minimization of a residual polynomial. This approach complements work of H. Tal-Ezer, who by an application of Faber polynomials, generates a set of Richardson iteration parameters based on a criterion distinct from least squares. The leapfrog iteration can be used with either set of parameters.

In a joint effort with D. Nicol and J. Saltz, a random conjugate gradient method is being developed. A conjugate gradient driver was assembled together with a conjugate gradient routine and a routine written to compute inner products by sampling. These program elements now form an undebugged package. An advantage of sampling for inner products and norms is that it may help with communication, I/O, or memory access overheads.

Paul Saylor, Joel H. Saltz, and David M. Nicol

A reduction in the asymptotic computational complexity of a number of common iterative methods appears, in some cases, to be achievable through a simple modification of the algorithms. Statistical estimation techniques are exploited in order to reduce the computation required in the calculation of the inner products required in the conjugate gradient method and of iteration matrix eigenvalues required for implementation of optimal Chebyshev acceleration. The size of the sample required for the statistical estimation and, consequently, the computation required to form the statistical estimate vary with the precision required of the estimate. Methods of determining sample size given a priori and observed measures of the problem behavior are being investigated. The utility of sampling in the estimation of inner products and iteration matrix eigenvalues is significant in the solution of very large scale problems involving millions of variables. Experimental work to elucidate the usefulness of these methods on vector and multiprocessor architectures is being carried out.

Ke-Gang Shih and Shlomo Ta'asan

Bifurcation problems of a bottom-heated box filled with incompressible fluid is studied numerically. Asymptotic analysis of this problem shows that the linearized problem has a very closely spaced spectrum. The method of multigrid Ritz projection, introduced by Brandt, McCormick, and Ruge (1983), is used. We also plan to treat imperfect bifurcation in the future.

Charles G. Speziale

Correlations of recently developed subgrid scale models for the large-eddy simulation of compressible turbulent flows have been completed in collaboration with M. Y. Hussaini, T. Zang (High-Speed Aerodynamics Division, LaRC), and G. Erlebacher (High-Speed Aerodynamics Division, LaRC). Work on the large-eddy simulation of homogeneous compressible turbulent flows with simple

shear is currently underway. Some preliminary investigations of possible large-eddy simulations by renormalization group methods have also been conducted. Applications of this work to the large eddy simulation of turbulent flow past a flat plate at high Mach numbers (with shock waves) are planned.

Work on the development of improved second-order closure models for incompressible turbulent flows with in-plane curvature continues in collaboration with T. Gatski (High-Speed Aerodynamics Division, LaRC). Potential applications of this work to the field of aerodynamic drag reduction are envisioned.

Shlomo Ta´asan

Multigrid methods for bifurcation problems are under study. Methods for path following at regular and singular points, detection and location of singularities, switching branches at bifurcation points, locating envelope of singular points, etc., are in development. Basically, the self-adjoint case has been treated already with very good success. Extensions to nonself adjoint problems with possible applications to Navier-Stokes equations is the next goal.

Another direction is the development of multigrid methods for inverse problems. Here the study is focused now on problems involving the heat equation. Applications to Nondestructive Thermal Evaluation will be demonstrated.

Eitan Tadmor

We introduce a new type of spectrally-accurate dissipation, which controls the Cribbs-like oscillations in nonlinear hyperbolic equations with shock waves. Using ideas of compensated compactness, it is shown that spectral methods augmented with this type of dissipation yield highly-accurate converging solutions. Together with D. Gottlieb, we show how to make spectral recovery of solutions to hyperbolic systems with nonsmooth data. Away from

its singular support, the solution is recovered <u>weakly</u>, using appropriate pre- and post-processing. In fact, pre-processing can be avoided in most cases, despite the presence of low-order coupling terms which usually lead to low-order accurate ´shadowed´ regions. We discuss the question of entropy stability for conservative approximations to systems of conservation laws. Using the two ingredients of entropy variables and entropy conservative schemes, we are able to give precise identification of such schemes in terms of their numerical viscosity. As a result of this, we derive and rederive a host of examples for numerical viscosity coefficients which guarantee entropy stability as well as maintain second-order accuracy for systems of the above type.

We derive a new non-oscillatory <u>central difference</u> code for systems of conservation laws. The new method does not require the use of an approximate Riemann solver and hence can be easily implemented on arbitrary systems. Numerical experiments agree with the predicted second-order resolution.

Hillel Tal-Ezer

Frequently, during the process of solving a mathematical model numerically, we end up with a need to operate on a vector v by an operator which can be expressed as $f(A)$ where A is an NxN matrix (e.g., $\exp(A)$, $\sin(A)$, $1/A$). Except for very simple matrices, it is impractical to construct the matrix $f(A)$ explicitly; usually an approximation is used. In the present research, we develop an algorithm which uses a polynomial approximation to $f(A)$. It is reduced to a problem of approximating $f(z)$ by a polynomial in z where z belongs to the domain D in the complex plane which includes all the eigenvalues of A. This problem of approximation is approached by interpolating the function $f(z)$ in a certain set of points which is known to have some external properties. The approximation thus achieved is "almost best." Implementing the algorithm for some practical problems which result from P.D.E.´s is under investigation.

The iterative solution to a set of linear equations $Ax = b$ is a well treated problem in the numerical analysis literature. While very efficient

algorithms have been developed for the case when A is a symmetric positive definite matrix, the general nonsymmetric case is still a challenging problem. Since a solution to a linear system is x = (1/A)b, implementing our algorithm for this problem is being investigated also.

Sherryl Tomboulian

Work is continuing on parallel graph embedding for SIMD architectures. With G. Erlebacher (High-Speed Aerodynamics Division, LaRC), an effort is underway to evaluate cellular automation for fluid flow problems, particularly for high Reynolds numbers. Work has also begun on developing graphically based methods for programming the Navier-Stokes Computer, a parallel architecture with reconfigurable pipelines.

Eli Turkel

Work continued on improving the Runge-Kutta multigrid algorithm to solve the steady state Euler and Navier-Stokes equations. We are currently investigating the effect of the artificial viscosity on both the accuracy and convergence rate of the scheme. The highly stretched meshes affect the implementation of the artificial viscosity in an anisotropic manner. Near the body, the mesh is very fine normal to the airfoil and relatively coarse tangential to the airfoil. In the farfield, the situation is reversed. Hence, the artificial viscosity must depend on the metrics of the gird. This dependency is especially important for viscous flows when one wants to resolve the boundary layer. An ICASE report, coauthored with R. Swanson, Jr. (Transonic Aerodynamics Division, LaRC), is presently being written. The results will be presented at the CFD conference in Hawaii.

The improvements introduced in the two-dimensional code are currently being extended to three space dimensions. In particular, three-dimensional viscous problems are starting to be analyzed using the multigrid version of the code. This project is being carried on jointly with V. Vatsa (Transonic

Aerodynamics Division, LaRC). In addition, both the two- and three-dimensional codes are being extensively documented. This description will appear in a future ICASE report.

Bram van Leer

Numerical flux functions for inviscid compressible flow can be distinguished by the number of characteristic waves they can recognize. Detailed formulas, such as those based on the "approximate Riemann solvers" of Roe and of Osher recognize all waves, which leads to a crisp representation of shocks and contact/slip discontinuities in steady solutions. A compromise is attained in van Leer's flux-split formula, which treats steady shocks equally as well as Osher's, but does not account for the linear discontinuities. Least accurate are the formulas that recognize only the largest characteristic speed, such as those advocated by Davis and by Yee. It appears that, for use in a Navier-Stokes code, the inviscid fluxes must be able to discern all characteristic waves. Numerical experiments on conical flows by J. Thomas (Low-Speed Aerodynamics Division, LaRC) show that van Leer's flux splitting requires four times as many zones across a boundary layer as Roe's flux-difference splitting, to get the proper temperature at an adiabatic wall. Other formulas have been and are being tested, including MacCormack's (with a code from R. W. Newsome); some findings will be presented at the AIAA 8th Computational Fluid Dynamics Conference in June 1987.

REPORTS AND ABSTRACTS

Dutt, Pravir and Shlomo Ta´asan: *A spline-based parameter estimation technique for static models of elastic structures*. ICASE Report No. 86-64, October 8, 1986, 33 pages. Submitted to Math. Comp.

We consider the problem of identifying the spatially varying coefficient of elasticity using an observed solution to the forward problem. Under appropriate conditions this problem can be treated as a first order hyperbolic equation in the unknown coefficient. We develop some continuous dependence results for this problem and propose a spline-based technique for approximating the unknown coefficient, based on these results. We establish the convergence of our numerical scheme and obtain error estimates.

Ta´asan, Shlomo and Pravir Dutt: *Parameter estimation problem for distributed systems using a multigrid method*. ICASE Report No. 86-65, October 8, 1986, 19 pages. Submitted to J. Comp. Physics.

We consider the problem of estimating spatially varying coefficients of partial differential equations from observation of the solution and of the right hand side of the equation. We assume that the observations are distributed in the domain and that enough observations are given. A method of discretization and an efficient multigrid method for solving the resulting discrete systems are described. Numerical results are presented for estimation of coefficients in an elliptic and a parabolic partial differential equation.

Myers, Thomas J. and Maya B. Gokhale: *Parallel scheduling of recursively defined arrays*. ICASE Report No. 86-66, October 3, 1986, 26 pages. Submitted to J. of Sym. Comp.

This paper describes a new method of automatic generation of concurrent programs which construct arrays defined by sets of recursive equations. We assume that the time of computation of an array element is a linear combination of its indices, and we use integer programming to seek a succession of hyperplanes along which array elements can be computed concurrently. The method can be used to schedule equations involving variable length dependency vectors and mutually recursive arrays. Portions of the work reported here have been implemented in the PS automatic program generation system.

Gokhale, Maya B.: *PS: A nonprocedural language with data types and modules*. <u>ICASE Report No. 86-67</u>, October 3, 1986, 20 pages. Submitted to J. of Sym. Comp.

The Problem Specification (PS) nonprocedural language is a very high level language for algorithm specification. PS is suitable for nonprogrammers, who can specify a problem using mathematically-oriented equations; for expert programmers, who can prototype different versions of a software system for evaluation; and for those who wish to use specifications for portions (if not all) of a program. PS has data types and modules similar to Modula-2. The compiler generates C code.

In this paper, we first show PS by example and then discuss efficiency issues in scheduling and code generation.

Napolitano, M. and J. H. Morrison: *Efficient solutions of two-dimensional incompressible steady viscous flows*. <u>ICASE Report No. 86-68</u>, October 16, 1986, 46 pages. Submitted to Computers and Fluids.

This paper provides a simple, efficient, and robust numerical technique for solving two-dimensional incompressible steady viscous flows at moderate-to-high Reynolds numbers. The proposed approach employs an incremental multigrid method and an extrapolation procedure based on minimum residual concepts to accelerate the convergence rate of a robust block-line-Gauss-Seidel solver for the vorticity-stream function Navier-Stokes equations.

Results are presented for the driven cavity flow problem using uniform and nonuniform grids and for the flow past a backward facing step in a channel. For this second problem, mesh refinement and Richardson extrapolation are used to obtain useful benchmark solutions in the full range of Reynolds numbers at which steady laminar flow is established.

Harten, A.: *On the nonlinearity of modern shock-capturing schemes*. <u>ICASE Report No. 86-69</u>, October 17, 1986, 62 pages. Submitted to Proc. of "Wave Motion: Modeling, theory and computations," U.C. Berkeley, June 1986; Springer-Verlag.

In this paper, we review the development of shock-capturing methods, paying special attention to the increasing nonlinearity in the design of numerical schemes. We study the nature of this nonlinearity and examine its relation to upwind differencing. This nonlinearity of the modern shock-capturing methods is essential, in the sense that linear analysis is not justified and may lead to wrong conclusions. Examples to demonstrate this point are given.

Banks, H. T. and I. G. Rosen: *Computational methods for the identification of spatially varying stiffness and damping in beams*. ICASE Report No. 86-70, October 22, 1986, 42 pages. Submitted to Control: Theory and Advanced Technology.

A numerical approximation scheme for the estimation of functional parameters in Euler-Bernoulli models for the transverse vibration of flexible beams with tip bodies is developed. The method permits the identification of spatially varying flexural stiffness and Voigt-Kelvin viscoelastic damping coefficients which appear in the hybrid system of ordinary and partial differential equations and boundary conditions describing the dynamics of such structures. An inverse problem is formulated as a least squares fit to data subject to constraints in the form of a vector system of abstract first order evolution equations. Spline-based finite element approximations are used to finite dimensionalize the problem. Theoretical convergence results are given and numerical studies carried out on both conventional (serial) and vector computers are discussed.

Banks, H. T., S. S. Gates, I. G. Rosen, and Y. Wang: *The identification of a distributed parameter model for a flexible structure*. ICASE Report No. 86-71, October 22, 1986, 43 pages. Submitted to SIAM J. Control and Opt.

We develop a computational method for the estimation of parameters in a distributed model for a flexible structure. The structure we consider (part of the "RPL experiment") consists of a cantilevered beam with a thruster and linear accelerometer at the free end. The thruster is fed by a pressurized hose whose horizontal motion effects the transverse vibration of the beam. We use the Euler-Bernoulli theory to model the vibration of the beam and treat the hose-thruster assembly as a lumped or point mass-dashpot-spring system at the tip. Using measurements of linear acceleration at the tip, we estimate the hose parameters (mass, stiffness, damping) and a Voigt-Kelvin viscoelastic structural damping parameter for the beam using a least squares fit to the data.

We consider spline based approximations to the hybrid (coupled ordinary and partial differential equations) system; theoretical convergence results and numerical studies with both simulation and actual experimental data obtained from the structure are presented and discussed.

Gibson, J. S. and I. G. Rosen: *Computational methods for optimal linear-quadratic compensators for infinite dimensional discrete-time systems*. ICASE Report No. 86-72, October 22, 1986, 25 pages. Submitted to Proc. of the Conf. on the Control and Identification of Distributed Parameter Systems, Vorau, Austria.

An abstract approximation theory and computational methods are developed for the determination of opitmal linear-quadratic feedback controls, observers and compensators for infinite dimensional discrete-time systems. Particular attention is paid to systems whose open-loop dynamics are described by semigroups of operators on Hilbert spaces. The approach taken is based upon the finite dimensional approximation of the infinite dimensional operator Riccati equations which characterize the optimal feedback control and observer gains. Theoretical convergence results are presented and discussed. Numerical results for an example involving a heat equation with boundary control are presented and used to demonstrate the feasibility of our methods.

Bennett, J. and P. Hall: *On the secondary instability of Taylor-Görtler vortices to Tollmien-Schlichting waves in fully-developed flows.* ICASE Report No. 86-73, November 17, 1986, 46 pages. Submitted to Journal of Fluid Mechanics.

There are many flows of practical importance where both Tollmien-Schlichting waves and Taylor-Görtler vortices are possible causes of transition to turbulence. In this paper, the effect of fully nonlinear Taylor-Görtler vortices on the growth of small amplitude Tollmien-Schlichting waves is investigated. The basic state considered is the fully developed flow between concentric cylinders driven by an azimuthal pressure gradient. It is hoped that an investigation of this problem will shed light on the more complicated external boundary layer problem where again both modes of instability exist in the presence of concave curvature. The type of Tollmien-Schlichting waves considered have the asymptotic structure of lower branch modes of plane Poisseulle flow. Whilst instabilities at lower Reynolds number are possible, the latter nodes are simpler to analyze and more relevant to the boundary layer problem. The effect of fully nonlinear Taylor-Görtler vortices on both two-dimensional and three-dimensional waves is determined. It is shown that, whilst the maximum growth as a function of frequency is not greatly affected, there is a large destabilizing effect over a large range of frequencies.

Tadmor, E.: *Convenient total variation diminishing conditions for nonlinear difference schemes.* ICASE Report No. 86-74, November 18, 1986, 32 pages. Submitted to SIAM J. Numerical Analysis.

Convenient conditions for nonlinear difference schemes to be total-variation diminishing (TVD) are derived. It is shown that such schemes share the TVD property, provided their numerical fluxes meet a certain positivity condition at extrema values but can be arbitrary otherwise. Our conditions are invariant under different incremental representations of the nonlinear schemes, and thus provide a simplified generalization of the TVD conditions due to Harten and others.

Roe, P. L.: *Remote boundary conditions for unsteady multidimensional aero-dynamic computations*. <u>ICASE Report No. 86-75</u>, November 18, 1986, 26 pages. Submitted to J. Comput. Phys.

We discuss the behavior of gas dynamic flows which are perturbations of a uniform stream in terms of information transfer across artificial (computational) boundaries remote from the source of disturbance. A set of boundary conditions is derived involving vorticity, entropy, and pressure-velocity relationships derived from bicharacteristic equations.

Banks, H. T. and K. Ito: *A numerical algorithm for optimal feedback gains in high dimensional LQR problems*. <u>ICASE Report No. 86-76</u>, November 18, 1986, 31 pages. Submitted to SIAM J. Control and Optimization.

We propose a hybrid method for computing the feedback gains in linear quadratic regulator problems. The method, which combines use of a Chandrasekhar type system with an iteration of the Newton-Kleinman form with variable acceleration parameter Smith schemes, is formulated so as to efficiently compute directly the feedback gains rather than solutions of an associated Riccati equation. The hybrid method is particularly appropriate when used with large dimensional systems such as those arising in approximating infinite dimensional (distributed parameter) control systems (e.g., those governed by delay-differential and partial differential equations). Computational advantage of our proposed algorithm over the standard eigenvector (Potter, Laub-Schur) based techniques are discussed and numerical evidence of the efficacy of our ideas presented.

Temam, Roger: *Survey of the status of finite element methods for partial differential equations*. <u>ICASE Report No. 86-77</u>, November 18, 1986, 63 pages. Submitted to the Proceedings of the Finite Element Workshop at Hampton, Virginia, Springer-Verlag.

The finite element methods (FEM) have proved to be a powerful method for the solution of boundary value problems associated to partial differential of either elliptic, parabolic, or hyperbolic type. They have also a good potential of utilization on parallel computers in relation in particular with the concept of domain decomposition.

This report is intended as an introduction to the FEM for the non-specialist. It contains a survey part which is totally nonexhaustive, and it also contains as an illustration, a report on some new results concerning two specific applications, namely a free boundary fluid-structure interaction problem, and the Euler equations for inviscid flows.

Nicolaides, R. A. and Shenaz Choudhury: *Iterative methods for elliptic finite element equations on general meshes*. ICASE Report No. 86-78, November 25, 1986. Submitted to the Proceedings of the Finite Element Workshop at Hampton, Virginia, Springer-Verlag.

This paper surveys iterative methods for arbitrary mesh discretizations of elliptic partial differential equations. The methods discussed are preconditioned conjugate gradients, algebraic multigrid, deflated conjugate gradients, an element-by-element technique, and domain decomposition. Computational results are included.

Ma, C. C. H.: *Inherent stability robustness of adaptive control systems*. ICASE Report No. 86-79, November 14, 1986, 39 pages.

Global stability robustness against unmodeled dynamics, arbitrary bounded internal noise as well as external disturbance is shown to exist for a class of discrete-time adaptive control systems when the regressor vector is persistently exciting. Although fast adaptation is definitely undesirable, slow adaptation is shown to be not necessarily beneficial for such global stability robustness. The entire analysis is good for systems with plants which need not be slowly varying.

Brenier, Yann and Stanley Osher: *The discrete one-sided Lipschitz condition for convex scalar conservation laws*. ICASE Report No. 86-80, November 25, 1986, 33 pages. Submitted to SIAM J. Numerical Analysis.

Physical solutions to convex scalar conservation laws satisfy a one-sided Lipschitz condition (OSLC) that enforces both the entropy condition and their variation boundedness. Consistency with this condition is therefore desirable for a numerical scheme and was proved for both the Godunov and the Lax-Friedrichs scheme—also, in a weakened version, for the Roe scheme, all of them being only first order accurate. A new, fully second order scheme is introduced here, which is consistent with the OSLC. The modified equation is considered and shows interesting features. Another second order scheme is then considered and numerical results are discussed.

Adams, Loyce, Randy LeVeque, and David Young: *Analysis of the SOR iteration for the 9-point Laplacian*. ICASE Report No. 86-81, December 8, 1986, 40 pages. Submitted to SIAM J. Numerical Analysis.

The SOR iteration for solving linear systems of equations depends upon an overrelaxation factor ω. A theory for determining ω was given by

Young [1950] for consistently ordered matrices. Here we determine the optimal ω for the 9-point stencil for the model problem of Laplace's equation on a square. We consider several orderings of the equations, including the natural rowwise and multicolor orderings, all of which lead to non-consistently ordered matrices, and find two equivalence classes of orderings with different convergence behavior and optimal ω's. We compare our results for the natural rowwise ordering to those of Garabedian [1956] and explain why both results are, in a sense, correct, even though they differ. We also analyze a pseudo SOR method for the model problem and show that it is not as effective as the SOR methods. Finally, we compare the point SOR methods to known results for line SOR methods for this problem.

Kopriva, David A.: *A practical assessment of spectral accuracy for hyperbolic problems with discontinuities.* ICASE Report No. 86-82, December 9, 1986, 22 pages. Submitted to J. Comp. Phys.

Physical and transform space filtering has been applied to the Fourier spectral collocation solution of the constant coefficient scalar wave equation with a discontinuous initial condition. High order accuracy can be extracted from the unfiltered solution. Smooth, high order Fourier space filtering gives expected polynomial order solutions away from the discontinuity. Spectral accuracy is observed with the physical space filter of Gottlieb and Tadmor.

Hall, Philip: *The nonlinear development of Gortler vortices in growing boundary layers.* ICASE Report No. 86-83, December 9, 1986, 52 pages. Submitted to J. Fluid Mech.

The development of Gortler vortices in boundary layers over curved walls in the nonlinear regime is investigated. The growth of the boundary layer makes a parallel flow analysis impossible except in the high wave-number regime so in general the instability equations must be integrated numerically. Here the spanwise dependence of the basic flow is described using Fourier series expansion whilst the normal and streamwise variations are taken into account using finite differences. The calculations suggest that a given disturbance imposed at some position along the wall will eventually reach a local equilibrium state essentially independent of the initial conditions. In fact, the equilibrium state reached is qualitatively similar to the large amplitude high wave-number solution described asymptotically by Hall (1982b). In general, it is found that the nonlinear interactions are dominated by a 'mean field' type of interaction between the mean flow and the fundamental. Thus, even though higher harmonics of the fundamental are necessarily generated, most of the disturbance energy is confined to the mean flow correction and the fundamental. A major

result of our calculations is the finding that the downstream velocity field develops a strongly inflectional character as the flow moves downstream. The latter result suggests that the major effect of Gortler vortices on boundary layers of practical importance might be to make them highly receptive to rapidly growing Rayleigh modes of instability.

Kamowitz, David: *Multigrid applied to singular perturbation problems*. ICASE Report No. 87-1, January 7, 1987. Submitted to Applied Mathematics and Computation.

The solution of the singular perturbation problem

$$-\varepsilon u'' + b(x)u' = f, \qquad 0 < x < 1$$

with

$$1 >> \varepsilon \, 0, \quad u(0) = u_0, \quad u(1) = u_1$$

by a multigrid algorithm is considered. Theoretical and experimental results for a number of different discretizations are presented. The theoretical and observed rates agree with the results developed in an earlier work of Kamowitz and Parter.

In addition, the rate of convergence of the algorithm when the coarse grid operator is the natural finite difference analogue of the fine grid operator is presented. This is in contrast to the case in the previous work where the Galerkin choice $(I_h^H L_h I_H^h)$ was used for the coarse grid operators.

Jackson, T. L., A. K. Kapila, and D. S. Stewart: *Evolution of a localized thermal explosion in a reactive gas*. ICASE Report No. 87-2, January 8, 1987, 62 pages. Submitted to SIAM J. of Applied Math.

Experimental observations of ignition in premixed gaseous reactants indicate that perfectly homogeneous initiation is practically unrealizable. Instead, combustion first sets in, as a rule, at small, discrete sites where inherent inhomogeneities cause chemical activity to proceed preferentially and lead to localized explosions. Combustion waves propagating away from these "hot spots" or "reaction centers" eventually envelope the remaining bulk.

This study examines the spatial structure and temporal evolution of a hot spot for a model involving Arrhenius kinetics. The hot spot, characterized by peaks in pressure and temperature with little diminution in local density, is shown to have one of two possible self-similar structures. The analysis employs a combination of asymptotics and numerics and terminates when pressure and temperature in the explosion have peaked.

Spall, R. E., T. B. Gatski, and C. E. Grosch: *On a criterion for vortex breakdown*. ICASE Report No. 87-3, January 8, 1987, 23 pages. Submitted to Physics of Fluids.

A criterion for the onset of vortex breakdown is proposed. Based upon previous experimental, computational, and theoretical studies, an appropriately defined local Rossby number is used to delineate the region where breakdown occurs. In addition, new numerical results are presented which further validate this criterion. A number of previous theoretical studies concentrating on inviscid standing-wave analyses for trailing wing-tip vortices are reviewed and reinterpreted in terms of the Rossby number criterion. Consistent with previous studies, the physical basis for the onset of breakdwon is identified as the ability of the flow to sustain such waves. Previous computational results are reviewed and re-evaluated in terms of the proposed breakdown criterion. As a result, the cause of breakdown occurring near the inflow computational boundary, common to several numerical studies, is identified. Finally, previous experimental studies of vortex-breakdown for both leading edge and trailing wing-tip vortices are reviewed and quantified in terms of the Rossby number criterion.

Lohner, Rainald, Ken Morgan, Jaime Peraire, and Mehdi Vahdati: *Finite element flux-corrected transport (FEM-FCT) for the Euler and Navier-Stokes equations*. ICASE Report No. 87-4, January 15, 1987, 25 pages. Submitted to Internat. J. Numer. Methods Fluids.

A high resolution finite element method for the solution of problems involving high speed compressible flows is presented. The method uses the concepts of flux-corrected transport and is presented in a form which is suitable for implementation on completely unstructured triangular or tetrahedral meshes. Transient and steady state examples are solved to illustrate the performance of the algorithm.

Naik, Vijay and Shlomo Ta´asan: *Performance studies of the multigrid algorithms implemented on hypercube multiprocessor systems*. ICASE Report No. 87-5, January 16, 1987, 21 pages. Submitted to Proc. of the 2nd Hypercube Multiprocessor Conference.

In this paper, we analyze and compare the performance on a hypercube multiprocessor of some of the major multigrid techniques used in practice. The model problem considered here is that of solving the 2-D incompressible Navier-Stokes equations representing the flow between two parallel plates. Results obtained by implementing the different multigrid schemes on an iPSC are presented. Effects on the overall performance of various parameters of the algorithms, of the partitioning strategies

employed, and of some of the characteristics of the underlying architecture are discussed.

Roe, P. L.: *Error estimates for cell-vertex solutions of the compressible Euler equations.* ICASE Report No. 87-6, January 22, 1987, 42 pages. Submitted to AIAA J.

The cell-vertex schemes due to Ni and Jameson, et al. have been subjected to a theoretical analysis of their truncation error. The analysis confirms the authors' claims for second-order accuracy on smooth grids, but shows that the same accuracy cannot be obtained on arbitrary grids. It is shown that the schemes have a unique generalization to axisymmetric flow that preserves the second-order accuracy.

Reneke, J. A. and R. E. Fennell: *RKH space approximations for the feedback operator in a linear hereditary system.* ICASE Report No. 87-8, February 3, 1987, 23 pages. Submitted to Internat. J. Control.

Computational implementation of feedback control laws for linear hereditary systems requires the approximation of infinite dimensional feedback operators with finite dimensional operators. The dense subspaces of K-polygonal functions in reproducing kernel Hilbert spaces, RKH spaces, suggest finite dimensional approximations of the matrix representations of the control operators. A convergence theorem is developed for the approximations, and the numerical implementation of the approximations is discussed.

Hussaini, M. Y.: *Stability, transition, and turbulence.* ICASE Report No. 87-9, February 27, 1987, 20 pages. Submitted to Proceedings of the NASA Conference on Supercomputing in Aerospace.

A glimpse is provided of the research program in stability, transition and turbulence based on numerical simulations. This program includes both the so-called abrupt and the restrained transition processes. Attention is confined to the prototype problems of channel flow and the parallel boundary layer in the former category and the Taylor-Couette flow in the latter category. It covers both incompressible flows and supersonic flows. Some representative results are presented.

Banks, H. T., R. K. Powers, and I. G. Rosen: *Inverse problems in the modeling of vibrations of flexible beams*. ICASE Report No. 87-10, February 27, 1987, 23 pages. Submitted to Proceedings of the Conference on Control Theory for Distributed Parameter Systems and Applications, Vorau, Austria, July 7-11, 1986.

The formulation and solution of inverse problems for the estimation of parameters which describe damping and other dynamic properties in distributed models for the vibration of flexible structures is considered. Motivated by a slewing beam experiment, the identification of a nonlinear velocity dependent term which models air drag damping in the Euler-Bernoulli equation is investigated. Galerkin techniques are used to generate finite dimensional approximations. Convergence estimates and numerical results are given. The modeling of, and related inverse problems for the dynamics of a high pressure hose line feeding a gas thruster actuator at the tip of a cantilevered beam, are then considered. Approximation and convergence are discussed and numerical results involving experimental data are presented.

Propst, Georg: *Piecewise linear approximation for hereditary control problems*. ICASE Report No. 87-11, February 27, 1987, 74 pages. Submitted to SIAM J. Control Optim.

This paper presents finite dimensional approximations for linear retarded functional differential equations by use of discontinuous piecewise linear functions. The approximation scheme is applied to optimal control problems when a quadratic cost integral has to be minimized subject to the controlled retarded system. It is shown that the approximate optimal feedback operators converge to the true ones both in case the cost integral ranges over a finite time interval as well as in the case it ranges over an infinite time interval. The arguments in the latter case rely on the fact that the piecewise linear approximations to stable systems are stable in a uniform sense. This feature is established using a vector-component stability criterion in the state space $\mathbb{R}^n \times L^2$ and the favorable eigenvalue behavior of the piecewise linear approximations.

Keeling, Stephen L.: *On Lipschitz continuity of nonlinear differential operators*. ICASE Report No. 87-12, March 17, 1987, 12 pages. Submitted to SIAM J. Numer. Anal.

In connection with approximations for nonlinear evolution equations, it is standard to assume that nonlinear terms are at least locally Lipschitz continuous. However, it is shown here that $f = f(x, \nabla u(x))$ is Lipschitz continuous from the subspace $W^{1,\infty} L_2$ into $W^{-1,2}$, and maps $W^{2,\infty}$ into $W^{1,\infty}$, if and only if f is affine with $W^{1,\infty}$ coefficients. In fact, a local version of this claim is proved.

Keeling, Stephen L.: *Galerkin/Runge-Kutta discretizations for semilinear parabolic equations.* ICASE Report No. 87-13, March 17, 1987, 31 pages. Submitted to SIAM J. Numer. Anal.

A new class of fully discrete Galerkin/Runge-Kutta methods is constructed and analyzed for semilinear parabolic initial boundary value problems. Unlike any classical counter part, this class offers arbitrarily high, optimal order convergence. In support of this claim, error estimates are proved, and computational results are presented. Furthermore, it is noted that special Runge-Kutta methods allow computations to be performed in parallel so that the final execution time can be reduced to that of a low order method.

Tomboulian, Sherryl: *A system for routing arbitrary directed graphs on SIMD architectures.* ICASE Report No. 87-14, March 18, 1987, 24 pages. Submitted to IEEE Trans. Comput.

There are many problems which can be described in terms of directed graphs that contain a large number of vertices where simple computations occur using data from connecting vertices. A method is given for parallelizing such problems on an SIMD machine model that is bit-serial and uses only nearest neighbor connections for communication. Each vertex of the graph will be assigned to a processor in the machine. Algorithms are given that will be used to implement movement of data along the arcs of the graph. This architecture and algorithms define a system that is relatively simple to build and can do graph processing. All arcs can be transversed in parallel in time $O(T)$, where T is empirically proportional to the diameter of the interconnection network times the average degree of the graph. Modifying or adding a new arc takes the same time as parallel traversal.

Brezzi, F.: *A survey of mixed finite element methods.* ICASE Report No. 87-15, March 18, 1987, 32 pages. Submitted to Proc. Workshop on Finite Element Methods, Theory, and Application, Springer-Verlag.

This paper is an introduction to and an overview of mixed finite element methods. It discusses the mixed formulation of certain basic problems in elasticity and hydrodynamics. It also discusses special techniques for solving the discrete problem.

Hall, Philip and William D. Lakin: *The fully nonlinear development of Gortler vortices in growing boundary layers.* ICASE Report No. 87-16, March 19, 1987, 35 pages. Submitted to Proc. Roy. Soc. Ser. (A).

The fully nonlinear development of small wavelength Gortler vortices in a growing boundary layer is investigated using a combination of asymptotic and numerical methods. The starting point for the analysis is the weakly nonlinear theory of Hall (1982b) who discussed the initial development of small amplitude vortices in a neighborhood of the location where they first become linearly unstable. That development is unusual in the context of nonlinear stability theory in that it is not described by the Stuart-Watson approach. In fact the development is governed by a pair of coupled non-linear partial differential evolution equations for the vortex flow and the mean flow correction. Here the further development of this interaction is considered for vortices so large that the mean flow correction driven by them is as large as the basic state. Surprisingly it is found that such a nonlinear interaction can still be described by asymptotic means. It is shown that the vortices spread out across the boundary layer and effectively drive the boundary layer. In fact the system obtained by writing down the equations for the fundamental vortex generate a differential equation for the basic state. Thus the mean flow adjusts so as to make these large amplitude vortices locally neutral. Moreover in the region where the vortices exist, the mean flow has a ´square-root´ profile and the vortex velocity field can be written down in closed form. The upper and lower boundaries of the region of vortex activity are determined by a free-boundary problem involving the boundary layer equations. In general it is found that this region ultimately includes almost all of the original boundary layer and much of the free-stream. In this situation the mean flow has essentially no relationship to the flow which exists in the absence of the vortices.

Jackson, T. L. and M. Y. Hussaini: *An asymptotic analysis of supersonic reacting mixing layers*. ICASE Report No. 87-17, March 19, 1987, 16 pages. Submitted to Combustion Science and Technology.

The purpose of this paper is to present an asymptotic analysis of the laminar mixing of the simultaneous chemical reaction between parallel supersonic streams of two reacting species. The study is based on a one-step irreversible Arrhenius reaction and on large activation energy asymptotics. Essentially it extends the work of Linan and Crespo to include the effect of free shear and Mach number on the ignition regime, the deflagration regime, and the diffusion flame regime. It is found that the effective parameter is the product of the characteristic Mach number and a shear parameter.

Scheurer, B.: *Remarks on the stability analysis of reactive flows*. ICASE Report No. 87-18, March 20, 1987, 21 pages. Submitted to Proc. Conference on Mathematical Modeling in Combustion, Lyon, France, April 27-30, 1987.

We study a simple model of compressible reacting flow. First, we derive a dispersion relation for the linearized problem, making a distinction between frozen and equilibrium sound speed. Second, we study the stability of the Von Neumann-Richtmyer scheme applied to this model. One finds a natural generalization of the C.F.L. condition.

Hariharan, S. I. and P. K. Dutt: *Acoustic gravity waves: A computational approach.* ICASE Report No. 87-19, March 24, 1987, 26 pages. Submitted to Applied Numerical Mathematics.

This paper discusses numerical solutions of a hyperbolic initial boundary value problem that arises from acoustic wave propagation in the atmosphere. Field equations are derived from the atmospheric fluid flow governed by the Euler equations. The resulting original problem is non-linear. A first order linearized version of the problem is used for computational purposes. The main difficulty in the problem as with any open boundary problem is in obtaining stable boundary conditions. Approximate boundary conditions are derived and shown to be stable. Numerical results are presented to verify the effectiveness of these boundary conditions.

Erlebacher, G., M. Y. Hussaini, C. G. Speziale, and T. Zang: *Toward the large-eddy simulation of compressible turbulent flows.* ICASE Report No. 87-20, March 30, 1987, 38 pages. Submitted to J. Fluid Mechanics.

New subgrid-scale models for the large-eddy simulation of compressible turbulent flows are developed based on the Favre-filtered equations of motion for an ideal gas. A compressible generalization of the linear combination of the Smagorinsky model and scale-similarity model (in terms of Favre-filtered fields) is obtained for the subgrid-scale stress tensor. An analogous thermal linear combination model is also developed for the subgrid-scale heat flux vector. The three dimensionless constants associated with these subgrid-scale models are obtained by correlating with the results of direct numerical simulations of compressible isotropic turbulence performed on a 96^3 grid using Fourier collocation methods. Extensive comparisons between the direct and modeled subgrid-scale fields are provided in order to validate the models. Future applications of these compressible subgrid-scale models to the large-eddy simulation of supersonic aerodynamic flows are discussed briefly.

ICASE COLLOQUIA

October 24   **Dr. David Middleton,** University of North Carolina – Chapel Hill: *Program Representation in the FFP Machine*

November 3   **Professor Alan Wolf,** The Cooper Union School of Engineering: *Diagnostics for Chaos*

November 4   **Dr. Edward A. Spiegel,** Columbia University: *Intermittency and Lacunarity in Turbulence*

November 10   **Dr. Cyrus K. Aidun,** Cornell University: *Structure and Onset of Oscillatory Rayleigh-Benard Convection in Porous Media*

November 17 18   **Professor Dave Levermore,** Brown University: *The Lattice Gas Cellular Automata Approach to Computational Hydrodynamics*

November 20   **Professor Paul Saylor,** University of Illinois at Urbana: *A Taxonomy for Conjugate Gradient Methods*

December 8   **Mr. Marco M. Mostrel,** University of California, Los Angeles: *Some Numerical Schemes for Transonic Flow Problems*

January 20   **Professor Thorwald Herbert,** Virginia Polytechnic Institute and State University: *Three Dimensional Instability of Boundary Layers*

February 5   **Professor Dieter Forster,** Temple University: *Randomly Stirred Fluids and the Renormalization Group*

February 11   **Professor Seymour Parter,** University of Wisconsin: *On Preconditioning*

February 12   **Mr. Luigi Martinelli,** Princeton University: *Calculation of Viscous Flow with Multigrid*

February 19   **Professor Hillel Tal-Ezer,** Tel-Aviv University: *A New Iterative Method for the Solution of $Ax = b$ Where A is a General Non-Symmetric Matrix*

February 23   **Professor Walid Abu–Sufah,** Virginia Polytechnic Institute and State University: *Workload Characterization for Vector Multiprocessors*

March 4   **Professor Matania Ben–Artzi,** Technion University, Israel: *A High-Resolution Numerical Scheme for Reactive Flows*

March 9   **Professor Bertil Gustafsson,** Stanford University: *Far Field Boundary Conditions for Hyperbolic Systems*

March 16 17   **Professor H. Jerome Keisler,** University of Wisconsin: *An Introduction to Nonstandard Analysis*

March 25   **Professor Alan George,** University of Tennessee: *Sparse Cholesky Factorization on a Local-Memory Multiprocessor*

March 26 27   **Professor Terry Pratt,** University of Virginia: *The PISCES 2 Parallel Programming Environment*

March 30   **Mr. Nathaniel Whitaker,** University of California, Berkeley: *A Numerical Solution of the Hele-Shaw Equations*

OTHER ACTIVITIES

A Workshop on Dynamic Workload Balancing was held October 20-21, 1986, at ICASE, NASA Langley Research Center, Hampton, Virginia. The purpose of this workshop was to bring people from varying backgrounds together to discuss different manifestations of the load balancing problem. Seventeen researchers were invited to speak. The following speakers and their affiliations are listed below:

G. Adams, RIACS

B. Goldberg, Yale University

A. Greenbaum, New York University

B. Gross, Yale University

D. Jefferson, University of California, Los Angeles

H. Jordan, University of Colorado

D. Keyes, Yale University

E. Lazowska, University of Washington

W. Leland, Bell Communications Research

D. Nicol, ICASE

J. Saltz, Yale University

H. Schwetman, Microelectronics Computer Technology Corporation

K. Sevcik, University of Toronto

R. Smith, Duke University

J. Stankovic, University of Massachusetts

D. Towsley, University of Massachusetts

J. Zahorjan, University of Washington

A Workshop on Parallel Languages and Environments was held November 12-14, 1986, at the Williamsburg Hospitality House, Williamsburg, Virginia. The purpose of this workshop was to see where progress had been made and where gaps still exist for programming environments for parallel computing. Sixteen researchers were invited to speak. Their topics are listed below:

F. Allen, IBM T. J. Watson Research Center: "The Parallel Translater Project"

H. Dietz, Purdue University: "The Refined Language Approach to Programming Parallel Machines"

D. Gannon, Indiana University: "Program Restructuring for Large Scale Multiprocessors"

D. Gelernter, Yale University: "Portable Parallel Programming Environments: Linda (real), Symmetric Lisp (potential)

M. Heath, Oak Ridge National Laboratory: "Parallel Matrix Computations: Algorithms Performance and Portability"

W. Jalby, INRIA, France: "Parallel Numerical Algorithm Development for the CEDAR System"

P. Mehrotra, Purdue University: "Transforming BLAZE Programs for Multiprocessor Execution"

A. Norton, IBM T. J. Watson Research Center: "Parallel Programming Models for RP-3"

D. Padua, University of Illinois: "Recent Advances in Software Restructuring for Parallel Processing"

G. Pfister, IBM T. J. Watson Research Center: "RP3: The Research Parallel Processing Prototype"

T. Pratt, University of Virginia: "The PISCES 2 Parallel Programming Enviroments"

S. Skedzielewski, Lawrence Livermore National Laboratory: "The SISAL Language and Its Implementations"

B. Smith, Supercomputing Research Center: "Shared Memory, Vectors, Message-Passing and Scalability"

L. Snyder, University of Washington: "Type Architectures"

D. Sorensen, Argonne National Laboratory: "SCHEDULE: An Aid to Writing Explicitly Parallel Programs in Fortran"

G. W. Stewart, University of Maryland: "Domino and Message-Passing"

A Workshop on Stability Theory was held November 21, 1986, at ICASE, NASA
Langley Research Center, Hampton, Virginia. The purpose of this workshop was
to discuss stability theory for growing boundary layers. Six researchers were
invited to speak; they are listed below along with their affiliations:

P. Hall, Exeter University

T. Herbert, Virginia Polytechnic Institute and State University

A. Nayfeh, Virginia Polytechnic Institute and State University

H. Reed, Arizona State University

W. Saric, Arizona State University

F. Smith, University College London

A Workshop on Stability and Transition of High Mach Number Shear Layers hosted by ICASE/NASA was held March 20, 1987, at ICASE, NASA Langley Research Center, Hampton, Virginia. The purpose of the workshop was to summarize the state of knowledge of high speed transition and highlight the outstanding problems. Eight researchers were invited to speak; they are listed below along with their affiliations:

S. Bogdonoff, Princeton University

D. Bushnell, NASA Langley Research Center

T. Herbert, Virginia Polytechnic Institute and State University

L. Mack, Jet Propulsion Laboratory

M. Morkovin, Illinois Institute of Technology

H. Reed, Arizona State University

E. Reshotko, Case Western University

W. Saric, Arizona State University

ICASE STAFF

I. ADMINISTRATIVE

Robert G. Voigt, Director
Ph.D., Mathematics, University of Maryland, 1969
Numerical Algorithms for Parallel Computers

Linda T. Johnson, Office and Financial Administrator

Etta M. Blair, Personnel/Bookkeeping Secretary

Barbara A. Cardasis, Administrative Secretary

Sidney A. Chappell, Technical Publications/Summer Housing Secretary
  (Through October 1986)

Carla J. Hult, Office Assistant
  (Through February 1987)

Barbara R. Stewart, Technical Publications Secretary

Emily N. Todd, Executive Secretary/Visitor Coordinator

II. SCIENCE COUNCIL for APPLIED MATHEMATICS and COMPUTER SCIENCE

Bruce Arden, Chairman and Arthur Doty Professor, Department of Electrical
Engineering and Computer Science, Princeton University.

Andrew J. Callegari, Director, Theoretical & Mathematical Sciences Laboratory,
Exxon Research & Engineering Company.

Peter Denning, Director, RIACS, NASA/Ames Research Center.

Michael J. Flynn, Professor, Department of Electrical Engineering, Computer
Systems Laboratory, Stanford University.

Bernard Galler, Professor, Department of Computer and Communication Sciences
and Associate Director of the Computer Center, University of Michigan.

Anthony C. Hearn, Department Head, Department of Information Sciences, Rand
Corporation. (Through December 1986)

Herbert Keller, Professor, Physics, Math, and Astronomy, California Institute
of Technology.

Seymour V. Parter, Professor, Department of Mathematics, University of
Wisconsin. (Through December 1986)

Werner C. Rheinboldt, Andrew W. Mellon Professor, Department of Mathematics and Statistics, University of Pittsburgh. (Through December 1986)

Robert G. Voigt, Director, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

III. ASSOCIATE MEMBERS

Saul S. Abarbanel, Professor, Department of Applied Mathematics, Tel-Aviv University, Israel.

H. Thomas Banks, Professor, Division of Applied Mathematics, Brown University.

David Gottlieb, Professor, Division of Applied Mathematics, Brown University.

Peter D. Lax, Professor, Courant Institute of Mathematical Sciences, New York University.

Merrell L. Patrick, Professor, Department of Computer Science, Duke University.

William R. Sears, Professor, Department of Aerospace and Mechanical Engineering, University of Arizona.

IV. CHIEF SCIENTIST

M. Yousuff Hussaini - PH.D., Mechanical Engineering, University of California, 1970. Computational Fluid Dynamics. (Beginning April 1978)

V. SENIOR STAFF SCIENTIST

Milton E. Rose - Ph.D., Mathematics, New York University, 1953. Numerical Methods. (January 1986 to December 1986)

VI. SCIENTIFIC STAFF

Thomas W. Crockett - B.S., Mathematics, College of William and Mary, 1977. Parallel Systems Research.

56

Pravir K. Dutt - Ph.D., Mathematics, University of California, Los Angeles, 1985. Numerical Analysis related to Navier-Stokes Equations. (July 1985 to September 1988)

David Kamowitz - Ph.D., Computer Science, University of Wisconsin, Madison, 1986. Iterative Methods for Numerical Solutions of Partial Differential Equations. (September 1986 to September 1988)

Stephen L. Keeling - Ph.D., Mathematics, University of Tennessee, 1986. Analysis of Methods for the Solution of Parabolic Partial Differential Equations. (September 1986 to September 1988)

Fumio Kojima - Ph.D., Control Theory, Kyoto University, Japan, 1985. Probabilistic and Stochastic Methods for Optimal Control Problems. (September 1986 to September 1988)

Chris Chen-Hsing Ma - Ph.D., Control Theory, University of Waterloo, Ontario, Canada, 1986. Numerical Technique for Problems in Adaptive Control. (July 1986 to July 1988)

Dimitri Mavriplis - Ph.D., Mechanical and Aerospace Engineering, Princeton University, 1987. Grid Techniques for Computational Fluid Dynamics. (February 1987 to February 1989)

Nessan Mac Giolla Mhuiris - Ph.D., Theoretical and Applied Mechanics, Cornell University, 1986. Theoretical and Numerical Models of Vortex Breakdown. (October 1985 to September 1988)

David J. Middleton - Ph.D., Computer Science, University of North Carolina, 1986. Design of Parallel Computing Systems. (November 1986 to November 1988)

Vijay K. Naik - M.S., Mechanical Engineering, University of Florida, 1982. AM., Computer Science, Duke University, 1984. Parallel Processing, Computational Fluid Dynamics. (August 1984 to December 1986)

David M. Nicol - Ph.D., Computer Science, University of Virginia, 1985. Techniques for Mapping Algorithms onto Parallel Computing Systems. (September 1985 to Septembr 1988)

Douglas H. Peterson - B.S., Computer Science, Christopher Newport College, 1984. Computer Systems. (October 1985 to September 1988)

Georg Propst - Ph.D., Mathematics-Functional Analysis, Karl Franzens Universitat, Austria, 1985. Linear Quadratic Control Problem for Delay Systems. (September 1985 to August 1987)

Ke-Gang Shih - Ph.D., Applied Mathematics, University of Maryland, 1985. Analysis of Methods to Treat Problems in Nonlinear Elasticity. (August 1985 to July 1987)

Shlomo Ta´asan - Ph.D., Applied Mathematics, Weizman Institute of Science, Israel, 1984. Multigrid Methods. (October 1984 to September 1987)

Sherryl J. Tomboulian - Ph.D., Computer Science, Duke University, 1986. Dynamic Graph Embedding Algorithms. (September 1986 to September 1988)

VII. VISITING SCIENTISTS

Saul S. Abarbanel - Ph.D., Theoretical Aerodynamics, Massachusetts Institute of Technology, 1959. Professor, Department of Applied Mathematics, Tel-Aviv University, Israel. Numerical Analysis of Partial Differential Equations. (January to December 1987)

Robert E. Fennell - Ph.D., Mathematics, Univeristy of Iowa, 1969. Professor, Department of Mathematical Sciences, Clemson University. Analytical and Numerical Methods for the Analysis of Control Problems for Hereditary Systems. (August 1986 to May 1987)

Philip Hall - Ph.D., Mathematics, Imperial College, England, 1973. Professor, Department of Applied Mathematics, University of Exeter, England. Computational Fluid Dynamics. (March to April 1987)

Eitan Tadmor - Ph.D., Numerical Analysis, Tel-Aviv University, 1979. Senior Lecturer, Department of Applied Mathematics, Tel-Aviv University, Israel. Numerical Methods for Partial Differential Equations. (February to March 1987)

Hillel Tal-Ezer - Ph.D., Applied Mathematics, Tel-Aviv University, 1985. Instructor, Department of Mathematics, Tel-Aviv University, Israel. Spectral Methods for Partial Differential Equations. (February to March 1987)

Eli Turkel - Ph.D., Applied Mathematics, New York University, 1970. Associate Professor, Department of Applied Mathematics, Tel-Aviv University, Israel. (January - December 1987)

VIII. CONSULTANTS

Loyce M. Adams - Ph.D., Applied Mathematics, University of Virginia, 1983. Associate Professor, Department of Applied Mathematics, University of Washington. Numerical Methods for Parallel Computing Systems.

Ivo Babuska - Ph.D., Technical Sciences, Tech University, Prague, Czechoslovakia, 1952; Mathematics, Academy of Sciences, Prague, 1956; D.Sc., Mathematics, Academy of Science, Prague, 1960. Professor, Institute for Physical Science and Technology, University of Maryland. Numerical Methods for Partial Differential Equations.

58

Alvin Bayliss - Ph.D., Mathematics, New York University, 1975. Associate Professor, Technological Institute, Northwestern University. Numerical Methods for Partial Differential Equations.

Marsha J. Berger - Ph.D., Numerical Analysis, Stanford University, 1982. Research Associate, Courant Institute of Mathematical Sciences. Numerical Methods for Partial Differential Equations.

Achi Brandt - Ph.D., Mathematics, Weizmann Institute of Science, 1965. Professor, Applied Mathematics Department, Weizmann Institute of Science, Israel. Multigrid Methods.

Dennis W. Brewer - Ph.D., Mathematics, University of Wisconsin, Madison, 1975. Associate Professor, Department of Mathematical Sciences, University of Arkansas. Methods for Parameter Identification and Estimation.

John A. Burns - Ph.D., Mathematics, University of Oklahoma, 1973. Professor, Virginia Polytechnic Institute and State University. Numerical Methods in Feedback Control and Parameter Estimation.

Janice E. Cuny - Ph.D., Computer Science, University of Michigan, 1981. Assistant Professor, Department of Computer and Information Science, University of Massachusetts. Program Environments for Parallel Computing Systems.

Peter R. Eiseman - Ph.D., Mathematics, University of Illinois, 1970. Senior Research Scientist and Adjunct Professor, Department of Applied Physics and of Nuclear Engineering, Columbia University. Computational Fluid Dynamics.

Stefan Feyock - Ph.D., Computer Science, University of Wisconsin, 1971. Associate Professor, Department of Mathematics and Computer Science, College of William and Mary. Artificial Intelligence.

George J. Fix - Ph.D., Mathematics, Harvard University, 1968. Professor, Department of Mathematics, University of Texas at Arlington. Numerical Methods for Partial Differential Equations.

Joseph E. Flaherty - Ph.D., Applied Mechanics, Polytechnic Institute of Brooklyn, 1969. Professor and Chairman, Departments of Mathematical Sciences and Computer Science, Rensselaer Polytechnic Institute. Singular Perturbations, Numerical Analysis and Applied Mathematics.

Dennis B. Gannon - Ph.D., Computer Science, University of Illinois, 1980. Assistant Professor, Department of Computer Science, Indiana University at Bloomington. Numerical Methods and Software and Architecture Design.

James F. Geer - Ph.D., Applied Mathematics, New York University, 1967. Professor, Systems Science and Mathematical Sciences, Watson School of Engineering, Applied Science and Technology, SUNY-Binghamton. Perturbation Methods and Asymptotic Expansions of Solutions to Partial Differential Equations.

J. Steven Gibson - Ph.D., Engineering Mechanics, University of Texas at Austin, 1975. Associate Professor, Department of Mechanical, Aerospace and Nuclear Engineering, University of California at Los Angeles. Control of Distributed Systems.

Maya Gokhale - Ph.D., Computer Science, University of Pennsylvania, 1983. Assistant Professor, Department of Computer Science, University of Delaware. Nonprocedural Languages and Parallel Processing.

Chester E. Grosch - Ph.D., Physics - Fluid Dynamics, Stevens Institute of Technology, 1967. Professor, Department of Computer Science and Slover Professor, Department of Oceanography, Old Dominion University. Hydrodynamic Stability, Computational Fluid Dynamics, Unsteady Boundary Layers and Algorithms for Array Processors.

Max D. Gunzburger - Ph.D., Mathematics, New York University, 1969. Professor, Department of Mathematics, Carnegie-Mellon University. Fluid Dynamics and Numerical Methods for Partial Differential Equations.

Mohammed Hafez - Ph.D., Aerospace Engineering, University of Southern California, 1972. Professor, Department of Mechanical Engineering, University of California, at Davis. Numerical Methods for the Solution of the Equations of Aerodynamics.

Subramaniya I. Hariharan - Ph.D., Mathematics, Carnegie-Mellon University, 1980. Associate Professor, Department of Mathematical Sciences, University of Akron. Numerical Methods for Partial Differential Equations.

Amiram Harten - Ph.D., Mathematics, New York University, 1974. Associate Professor, Department of Mathematics, Tel-Aviv University, Israel. Numerical Solution for Partial Differential Equations.

Thorwald Herbert - Ph.D., Aerospace Engineering, University of Stuttgart, GERMANY, 1978. Professor, Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University. Fluid Dynamics.

Kazufumi Ito - Ph.D., Systems Science and Mathematics, Washington University, 1981. Assistant Professor, Division of Applied Mathematics, Brown University. Control Theory.

Thomas L. Jackson - Ph.D., Mathematics, Rensselaer Polytechnic Institute, 1985. Assistant Professor, Department of Mathematics, Old Dominion University. Numerical and Analytical Methods for Chemically Reacting Flows.

Antony Jameson - Ph.D., Magnetohydro-Dynamics, Cambridge University, England, 1963. James S. McDonnell Distinguished Professor, Department of Mechanical and Aerospace Engineering, Princeton University. Computational, Fluid Dynamics.

Harry F. Jordan - Ph.D., Physics, University of Illinois, 1977. Professor Department of Electrical and Computer Engineering, University of Colorado at Boulder. Parallel Computation.

Ashwani K. Kapila - Ph.D., Theoretical and Applied Mechanics, Cornell University, 1975. Associate Professor, Department of Mathematical Sciences, Rensselaer Polytechnic Institute. Ordinary and Partial Differential Equations, Asymptotic Methods.

David E. Keyes - Ph.D., Applied Mathematics, Harvard University, 1984. Assistant Professor, Mechanical Engineering, Yale University. Parallelizaton of Numerical Procedures Appropriate for the Study of Combustion.

David A. Kopriva - Ph.D., Applied Mathematics, University of Arizona, 1982. Assistant Professor, Department of Mathematics, Florida State University. Spectral Methods for Problems in Fluid Dynamics.

Robert Krasny - Ph.D., Applied Mathematics, University of California at Berkeley, 1983. NSF Fellow, Courant Institute, New York University. Vortex Sheet Evolution.

Heinz-Otto Kreiss - Ph.D., Mathematics, Royal Institute of Technology, Sweden 1960. Professor, Department of Applied Mathematics, California Institute of Technology. Numerical Analysis.

Karl K. Kunish - Ph.D., Mathematics, University of Graz, Austria. Associate Professor, Department of Mathematics, Technical University of Graz, Austria. Parameter Identification and Control.

William D. Lakin - Ph.D., Applied Mathematics, University of Chicago, 1968. Eminent Professor, Department of Mathematical Sciences, Old Dominion University. Fluid Mechanics and Elastic Vibrations.

Randall J. LeVeque - Ph.D., Computer Science, Stanford University, 1982. Assistant Professor Department of Mathematics, University of Washington. Numerical Solution of Partial Differential Equations.

Liviu R. Lustman - Ph.D., Applied Mathematics, Tel Aviv University, Israel, 1979. Scientist, Sterling Software, Ames Research Center. Methods for Partial Differential Equations.

Robert W. MacCormack - M.S., Mathematics, Stanford University. Professor, Department of Aeronautics and Astronautics, Stanford University. Computational Fluid Dynamics and Numerical Analysis.

Piyush Mehrotra - Ph.D., Computer Science, University of Virginia, 1982. Associate Professor, Department of Computer Science, Purdue University. Programming Languages for Multiprocessor Systems.

Katherine A. Murphy - Ph.D., Applied Mathematics, Brown University, 1983. Visiting Assistant Professor, Department of Applied Mathematics, Brown University. Control Theory and Estimation of Parameters.

Roy A. Nicolaides - Ph.D., Mathematics, University of London, 1972. Professor, Department of Mathematics, Carnegie-Mellon University. Numerical Solution of Partial Differential Equations.

Robert E. Noonan – Ph.D., Computer Science, Purdue University, 1971. Professor, Department of Computer Science, College of William and Mary. Parallel Programing Techniques.

Joseph E. Oliger – Ph.D., Numerical Analysis, Uppsala University, Sweden, 1973. Associate Professor, Department of Computer Science, Stanford University. Numerical Methods for Partial Differential Equations.

James M. Ortega – Ph.D., Mathematics, Stanford University, 1962. Professor and Chairman, Department of Applied Mathematics, University of Virginia. Numerical Methods for Partial Differential Equations.

Stanley J. Osher – Ph.D., Functional Analysis, New York University, 1966. Professor, Department of Mathematics, University of California at Los Angeles. Methods for the Numerical Analysis of Partial Differential Equations.

Anthony Patera – Ph.D., Applied Mathematics, Massachusetts Institute of Technology, 1982. Assistant Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology. Numerical Methods for Fluid Dynamics and Heat Transfer.

Terrence W. Pratt – Ph.D., Mathematics/Computer Science, University of Texas at Austin, 1965. Professor, Department of Computer Science, University of Virginia. Programming Languages.

Daniel A. Reed – Ph.D., Computer Science, Purdue University, 1983. Assistant Professor, Department of Computer Science, University of Illinois. Parallel Processing.

Helen L. Reed – Ph.D., Engineering Mechanics, Virginia Polytechnic Institute and State University, 1981. Associate Professor, Department of Mechanical Engineering, Arizona State University. Computional Fluid Dynamics.

Paul F. Reynolds – Ph.D., Computer Science, University of Texas at Austin, 1979. Assistant Professor, Department of Computer Science, The University of Virginia. Parallel Computing Systems.

I. Gary Rosen – Ph.D., Applied Mathematics, Brown University, 1980. Assistant Professor, Department of Applied Mathematics, University of Southern California. Numerical Methods for Problems in Control Systems.

Joel H. Saltz – Ph.D., Computer Science, Duke University, 1985. Assistant Professor, Yale University. Parallel Computing.

Paul E. Saylor – Ph.D., Mathematics, Rice University, 1986. Associate Professor, Computer Science Department, University of Illinois, Urbana. Iterative Solution of Linear Algebraic Equations and Algorithms for Parallel Computers.

Nancy E. Shoemaker – Ph.D., Mathematics, Rensselaer Polytechnic Institute, 1977. Assistant Administrator, Planning Research Corporation. Utilization of the Computational Resources.

Lawrence Sirovich - Ph.D., Fluid Mechanics, Johns Hopkins University, 1960. Professor, Division of Applied Mathematics, Brown University. Fluid Mechanics.

Charles G. Speziale - Ph.D., Aerospace and Mechanical Sciences, Princeton University, 1978. Associate Professor, Department of Mechanical Engineering, Georgia Institute of Technology. Turbulence Modeling.

Edward A. Spiegel - Ph.D, Astronomy, University of Michigan, 1958. Rutherford Professor of Astronomy, Department of Astronomy and Astrophysics, Columbia University. Mathematical Aspects of Turbulence.

John C. Strikwerda - Ph.D., Mathematics, Stanford University, 1976. Associate Professor, Department of Computer Sciences, University of Wisconsin-Madison. Numerical Methods for Partial Differential Equations.

Lu Ting - Ph.D., Aeronautics, New York University, 1951. Professor, Courant Institute of Mathematical Sciences, New York University. Fluid Mechanics.

Bram van Leer - Ph.D., Theoretical Astrophysic, Leiden State University, THE NETHERLANDS, 1970. Professor, Department of Aerospace Engineering, University of Michigan. Computational Fluid Dynamics.

John Van Rosendale - Ph.D., Computer Science, University of Illinois, 1980. Assistant Professor, Computer Science Department, University of Utah. Parallel Processing.

J. Christian Wild - Ph.D., Computer Science, Rutgers University, 1977. Assistant Professor, Department of Computer Science, Old Dominion University. Concurrent Computing Systems.

IX. STUDENT ASSISTANTS

William E. Diego - Graduate student at the College of William and Mary. (May 1986 to Present)

Raad A. Fatoohi - Graduate student at Old Dominion University. (September 1985 to Present)

Frank F. Willard - Graduate student at College of William and Mary. (August 1986 to Present)

1. Report No. NASA CR-178314	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Semiannual Report, October 1, 1986 through March 31, 1987		5. Report Date May 1987	
		6. Performing Organization Code	
7. Author(s)		8. Performing Organization Report No.	
9. Performing Organization Name and Address Institute for Computer Applications in Science and Engineering Mail Stop 132C, NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 505-90-21-01	
		11. Contract or Grant No. NAS1-18107	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Contractor Report	
		14. Sponsoring Agency Code	

15. Supplementary Notes

Langley Technical Monitor: J. C. South
Final Report

16. Abstract

This report summarizes research conducted at the Institute for Computer Applications in Science and Engineering in applied mathematics, numerical analysis, and computer science during the period October 1, 1986 through March 31, 1987.

17. Key Words (Suggested by Authors(s)) Mathematics Numerical Analysis Computer Science	18. Distribution Statement 59 – Mathematics and Computer Sciences (General) Unclassified – Unlimited		
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 66	22. Price A04